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RESEARCH MEMORANDUM

THE EFFECTS OF CENTRALLY MOUNTED WING-TIP TANKS ON THE SUBSONIC AERODYNAMIC CHARACTERISTICS OF A WING OF ASPECT RATIO 10 WITH 35° OF SWEEPBACK

By Bruce E. Tinling and W. Richard Kolk

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The effects of three centrally mounted wing-tip tanks on the aerodynamic characteristics of a cambered wing having an aspect ratio of 10 and 35° of sweepback were investigated. The three tip tanks had equal volumes and fineness ratios of 10, 6.67, and 5. The Reynolds number was varied from 2,000,000 to 10,000,000 at a Mach number of 0.25, and the Mach number was varied from 0.25 to 0.90 at a Reynolds number of 2,000,000. Lift, drag, and pitching moment were measured. The tip tanks reduced the maximum lift-drag ratio approximately 10 percent at a Mach number of 0.25 and a Reynolds number of 10,000,000. The reduction in drag-divergence Mach number caused by the tip tanks was small, the maximum reduction being about 0.02. In general, the reduction in the drag-divergence Mach number and in the lift-drag ratio at high Mach numbers caused by the tip tank having a fineness ratio of 10 was less than that caused by the tip tanks having fineness ratios of 6.67 and 5. At Mach numbers less than the drag-divergence Mach number the tip tanks caused an increase in static longitudinal stability indicated by a change in pitching-moment-curve slope $\partial C_m/\partial C_L$ of about -0.08. At low speeds, a vane near the tank-wing juncture alleviated flow separation near the juncture at Reynolds numbers of 6,000,000 and 10,000,000.

INTRODUCTION

The use of auxiliary fuel tanks mounted on the wing tips has been successful in extending the range of airplanes with unswept wings. Results of wind-tunnel tests have indicated that properly designed wing-tip fuel tanks may be used with unswept wings with very little change in the pitching-moment characteristics. In some instances (reference 1), an improvement in the drag at high lift coefficients was attained due to the increase in the effective aspect ratio resulting from the end-plate effects of the tip tanks. Data concerning the effects of external stores, including wing-tip tanks, on the aerodynamic characteristics of a tailless airplane having a wing with an aspect ratio of 3.01 and 35° of sweepback are presented in reference 2. The effects of bodies of revolution mounted on the tips of a wing having an aspect ratio of 3.5 and 63° of sweepback are presented in reference 3.

The present investigation was conducted in the Ames 12-foot pressure wind tunnel to evaluate the effects of centrally mounted wing-tip tanks having fineness ratios of 10, 6.67, and 5 on the aerodynamic characteristics of a cambered wing having an aspect ratio of 10 and 35° of sweepback. The results of tests of the semispan model wing without tip tanks have previously been reported in reference 4.

The tests were conducted over a range of Mach numbers from 0.25 to 0.90 at a Reynolds number of 2,000,000 and over a range of Reynolds numbers from 2,000,000 to 10,000,000 at a Mach number of 0.25.

NOTATION

C_D drag coefficient $\left(\frac{\text{drag}}{qS}\right)$

$C_{D_{o_{min}}}$ minimum profile-drag coefficient assuming elliptical span load distribution, minimum value of $\left(C_D - \frac{{C_L}^2}{\pi A}\right)$

C_L lift coefficient $\left(\frac{\text{lift}}{qS}\right)$

C_m pitching-moment coefficient about axis passing through the quarter point of the mean aerodynamic chord $\left(\frac{\text{pitching moment}}{qS\,\bar{c}}\right)$

C_{m_o} pitching-moment coefficient for zero lift

A aspect ratio $\left(\frac{b^2}{2S}\right)$

M Mach number $\left(\frac{V}{a}\right)$

R Reynolds number $\left(\frac{\rho V c}{\mu}\right)$

S semispan wing area, square feet

V airspeed, feet per second

L/D lift-drag ratio $\left(\frac{\text{lift}}{\text{drag}}\right)$

a speed of sound, feet per second

b span of complete wing, measured perpendicular to the plane of symmetry, feet

c chord, measured parallel to the plane of symmetry, feet

$\bar{c}$ mean aerodynamic chord $\left(\frac{\int_0^{b/2} c^2 dy}{\int_0^{b/2} c\, dy}\right)$, feet

q dynamic pressure, pounds per square foot

α angle of attack, degrees

α_o angle of attack for zero lift, degrees

ρ density of air, slugs per cubic foot

μ absolute viscosity, slugs per foot second

MODELS

The semispan model wing had 35° of sweepback of the quarter-chord line, a taper ratio of 0.5, and represented a wing of aspect ratio 10. The streamwise wing sections were the NACA 64_1A312 with a modified $a = 0.8$ mean line. (See reference 5.) The coordinates of the section are tabulated in table I. The three tip tanks were bodies of revolution having equal volumes and having fineness ratios of 10, 6.67, and 5. For each of the tanks, the longitudinal section containing the axis was that of an NACA 65A-series airfoil. (See table II.) Each tank was equipped with a vane, the purpose of which was to prevent flow separation at the tank-wing juncture. Details of the wing and tanks, and the position of the vane are shown in figure 1. The model wing and the tip tanks were furnished by the Lockheed Aircraft Corporation.

The turntable upon which the model was mounted in the wind tunnel is directly connected to the force-measuring apparatus. The model was mounted with the root chord in the plane of the turntable and the turntable-model juncture was sealed. A photograph of the model mounted in the wind tunnel and of a typical tip-tank installation is shown in figure 2.

TESTS

Two series of tests were conducted: one to evaluate the effects of compressibility at a constant Reynolds number, and one to evaluate the effects of Reynolds number at a low Mach number. Lift, drag, and pitching moment were measured over a range of angle of attack sufficient to obtain lift coefficients from less than zero to that for stall, except where the range was limited by the capacity of the force balance or by the strength of the model.

The tests to evaluate the effects of compressibility were conducted at Mach numbers from 0.25 to 0.90 and at a Reynolds number of 2,000,000. The tests to evaluate the effects of Reynolds number were conducted at a Mach number of 0.25 and at Reynolds numbers up to 10,000,000.

CORRECTIONS TO DATA

The data have been corrected for the effects of tunnel-wall interference, including constriction due to the presence of the tunnel walls, and approximately for model-support tare forces.

Corrections to the data for the effects of tunnel-wall interference originating from lift on the model have been evaluated by the methods of reference 6, using the theoretical span loading for incompressible flow calculated by the methods of reference 7. The corrections added to the drag and to the angle of attack were

$$\Delta\alpha = 0.295\ C_L$$

$$\Delta C_D = 0.00472\ {C_L}^2$$

Constriction effects due to the presence of the tunnel walls were computed by the methods of reference 8. These corrections have not been modified to allow for the effect of sweep. The magnitudes of the corrections to the Mach number and to the dynamic pressure are shown in the following table:

Corrected Mach number	Uncorrected Mach number	$\dfrac{q \text{ corrected}}{q \text{ uncorrected}}$
0.600	0.599	1.002
.700	.699	1.002
.750	.748	1.003
.800	.798	1.003
.825	.822	1.004
.850	.847	1.004
.875	.871	1.005
.900	.894	1.007

A correction to the drag data was made to allow for forces on the exposed surface of the turntable. This correction was determined from tests with the model removed from the tunnel. The following tare corrections were subtracted from the measured drag coefficients:

$R \times 10^{-6}$	M	$C_{D_{tare}}$
10	0.25	0.0044
6	.25	.0045
4	.25	.0046
2	.25	.0050
2	.40	.0053
2	.60	.0056
2	.70	.0058
2	.75	.0060
2	.80	.0062
2	.825	.0063
2	.85	.0064
2	.875	.0066
2	.90	.0067

No attempt was made to evaluate tares due to interference between the model and the turntable or to compensate for the tunnel-floor boundary layer which, at the location of the model, had a displacement thickness of one-half inch.

RESULTS AND DISCUSSION

Effects of Reynolds Number

The results of tests conducted to evaluate the effects of changing Reynolds number on the aerodynamic characteristics of the wing alone and of the wing and tip tank combinations are presented in figure 3. As reported in reference 4, decreasing the Reynolds number resulted in a reduction of lift over the outer sections of the wing. This reduction of lift caused a large change in the aerodynamic characteristics of the wing alone. As would be anticipated from these results, the effects of Reynolds number on the wing and tip tank combinations were also large.

The lift-drag ratios computed from the data shown in figure 3 are presented in figure 4. Inspection of these data reveals that the decrement of the lift-drag ratio caused by the tip tanks was dependent upon the test Reynolds number. At lift coefficients near that for the maximum lift-drag ratio, the tip tanks caused a greater decrease in the lift-drag ratio at a Reynolds number of 2,000,000 than at a Reynolds number of 10,000,000. At higher lift coefficients, increasing the Reynolds number had the opposite effect, the tanks causing a greater decrease in lift-drag ratio at a Reynolds number of 10,000,000 than at a Reynolds number of 2,000,000.

Effects of Wing-Tip Tanks at Low Subsonic Speeds

Only the data obtained at a Reynolds number of 10,000,000 will be considered in discussing the effects of tip tanks on the low-speed aerodynamic characteristics since these data are the most nearly representative of full-scale conditions. The data obtained at a Reynolds number of 10,000,000 and a Mach number of 0.25 are presented in figure 5. The values of some pertinent aerodynamic parameters as obtained from the data of this figure are presented in the following table:

Parameter	Wing alone	Wing and Tank		
		Fineness ratio 10	Fineness ratio 6.67	Fineness ratio 5
$^1(\partial C_L/\partial \alpha)_{\text{design } C_L}$	0.075	0.079	0.079	0.079
$(\partial C_m/\partial C_L)_{\text{design } C_L}$	−.046	−.124	−.150	−.150
$^2C_{L_{max}}$	1.24	1.27	− − −	1.27
C_{m_o}	−.048	−.050	−.046	−.048
α_o	−2.2	−2.1	−2.1	−2.1
C_{D_o}	.0060	.0069	.0069	.0070
$(L/D)_{max}$	34	31	31	30
C_L for $(L/D)_{max}$	.40	.42	.39	.35

[1]The design lift coefficient of the wing was approximately 0.25 (streamwise section design lift coefficient multiplied by the cosine of 35°).
[2]At R = 6,000,000 (fig. 3).

The increase in lift-curve slope of 0.004 per degree due to the tip tanks was primarily due to an increase in the effective aspect ratio caused by end-plate effects. Computations based on the lift of an isolated body of fineness ratio 9.9 (reference 9) indicate that the lift forces on the tanks could not account for an increase in the lift-curve slope of more than about 0.0003 per degree. Previous studies of wing and centrally mounted wing and tip tank combinations have, in some instances (reference 1), indicated a reduction in the induced drag due to an increase in the effective aspect ratio, which, at large lift coefficients, was sufficient to compensate for the drag of the tanks. The variation of $C_D - C_{D_{o_{min}}}$ with lift coefficient squared, presented in figure 6, shows that the value of $C_D - C_{D_{o_{min}}}$ was, in general, greater for the wing and tip tank combinations than for the wing alone. This indicates that the decrease in induced drag resulting from an increase in effective aspect ratio due to the tip tanks in the present investigation was not sufficient to compensate for the increases with lift coefficient in the profile drag due to the tank.

The tip tanks caused an increase of static longitudinal stability as is indicated by a change in the pitching-moment-curve slope $\partial C_m/\partial C_L$

of about -0.08. It should be noted, however, that on swept wings the weight of tip tanks and tip tank fuel is destabilizing since the installation is aft of the normal center of gravity. The aerodynamic effects therefore tend to counterbalance the mass effects of tip tanks.

As the lift coefficient was increased above about 0.3, the static longitudinal stability of the wing alone gradually became less. The static longitudinal stability of the wing and tip tank combinations, however, showed a more definite discontinuity as the lift coefficient was increased beyond about 0.3. (See fig. 5.)

Effect of Wing-Tip Tanks at High Subsonic Mach Numbers

The data obtained at Mach numbers from 0.25 to 0.90 at a Reynolds number of 2,000,000 are presented in figure 7. The effects of Mach number on the wing alone have previously been reported in reference 4.

The drag coefficient as a function of Mach number is presented in figure 8 for several values of lift coefficient. The Mach numbers for drag divergence, defined as the Mach number for which $\partial C_D/\partial M = 0.1$, are presented in the following table:

C_L	Wing alone	Fineness ratio 10	Fineness ratio 6.67	Fineness ratio 5
0	0.88	0.88	0.87	0.86
.2	.85	.84	.84	.83
.4	.82	.81	.80	.80
.6	.76	.76	.76	.75

In addition to having a higher drag-divergence Mach number than the other wing and tip tank combinations, the drag of the wing and tip tank of fineness ratio 10 was less than that of the other wing and tip tank combinations at the higher Mach numbers. The lower drag of the wing and tip tank having a fineness ratio of 10 is further illustrated in figure 9 where the variation of lift-drag ratio with lift coefficient is presented. Up to a Mach number of about 0.70, these data indicate no important differences between the lift-drag ratios of the three wing and tip tank combinations. At Mach numbers greater than 0.70, the lift-drag ratio was, in general, greater for the wing and tip tank combination with the tip tank having a fineness ratio of 10 and least for the combinations with the tip tank having a fineness ratio of 5.

The possible effect of Reynolds number must be considered when comparing the lift-drag ratios of the wing alone and the wing and tip tank combinations at high Mach numbers. The results of tests at a Mach number of 0.25 indicated a large effect of Reynolds number on the decrement in lift-drag ratio due to the tip tanks. If these effects prevail at the higher Mach numbers, the decrement in lift-drag ratio due to the tip tanks for lift coefficients near that for maximum lift-drag ratio will not be as great at full-scale Reynolds numbers as indicated by the data at a Reynolds number of 2,000,000. At greater lift coefficients, an increase in Reynolds number may cause an increase in the decrement in lift-drag ratio due to the tip tanks. (See fig. 4.)

The effects of tip tanks on the lift-curve slope and the pitching-moment-curve slope at high subsonic speeds are summarized in figure 10 for a lift coefficient of 0.25. For Mach numbers up to about that for drag divergence, the tip tanks increased the lift-curve slope by approximately 0.005 and caused the pitching-moment-curve slope $\partial C_m/\partial C_L$ to more negative by about 0.08, indicating an increase of static longitudinal stability. The tip tanks caused no significant change in the Mach number at which the abrupt decrease of lift-curve slope occurred. The tip tanks of fineness ratios 6.67 and 5, however, did decrease the Mach number at which a decrease of static longitudinal stability occurred.

Effectiveness of the Wing-Tip-Tank Vane

The aerodynamic characteristics of the wing and tip tank having a fineness ratio of 6.67 both with and without the tip-tank vane are presented in figures 11 and 12. The results at a Mach number of 0.25 and Reynolds numbers of 6,000,000 and 10,000,000 show that the vane alleviated the separation effects over the outer sections of the wing. This alleviation is evidenced by the larger negative value of pitching-moment coefficient, increased lift coefficients, and decreased drag coefficients at angles of attack greater than about 7° when the vane was in place. The effect of the vane at a Reynolds number of 2,000,000 at Mach numbers from 0.25 to 0.875 was small except at a Mach number of 0.70. At this Mach number, the lift coefficient at which a reduction of static longitudinal stability occurred was increased from about 0.5 to 0.7 by the vane.

CONCLUSIONS

The results of wind-tunnel tests to evaluate the effects of centrally mounted wing-tip tanks on the aerodynamic characteristics of a cambered wing having an aspect ratio of 10 with 35° of sweepback have been presented. These results indicated that:

1. The reduction in maximum lift-drag ratio due to the tip tanks was about 10 percent at a Reynolds number of 10,000,000 and a Mach number of 0.25. The decrement in the lift-drag ratio due to the tip tanks was dependent on the test Reynolds number.

2. The reduction in the drag-divergence Mach number due to the tip tanks was small, the greatest reduction observed being approximately 0.02. The reduction in the Mach number for drag divergence and in the lift-drag ratio at high Mach numbers was less for the tip tank having a fineness ratio of 10 than for those having fineness ratios of 6.67 and 5.

3. The tip tanks caused the pitching-moment-curve slope $\partial C_m/\partial C_L$ to be changed by about -0.08 at Mach numbers up to approximately the Mach number of drag divergence.

4. At low speeds and Reynolds numbers of 6,000,000 and 10,000,000 the vane near the tip tank and wing juncture alleviated the local separation.

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TABLE I

COORDINATES FOR THE NACA 64_1A312, a = 0.8 (MODIFIED) AIRFOIL SECTION

[Stations and ordinates given in percent of airfoil chord]

Upper Surface		Lower Surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.364	1.036	.636	.867
.598	1.267	.902	1.029
1.078	1.635	1.422	1.273
2.299	2.324	2.701	1.691
4.774	3.320	5.226	2.238
7.265	4.085	7.735	2.626
9.763	4.726	10.237	2.937
14.773	5.745	15.227	3.403
19.793	6.523	20.207	3.732
24.820	7.108	25.180	3.954
29.850	7.530	30.150	4.084
34.883	7.800	35.116	4.128
39.919	7.911	40.081	4.074
44.955	7.834	45.045	3.892
49.990	7.600	50.010	3.610
55.022	7.233	54.978	3.255
60.051	6.753	59.949	2.848
65.076	6.171	64.924	2.406
70.096	5.494	69.904	1.946
75.113	4.736	74.887	1.496
80.135	3.898	79.865	1.094
85.132	2.959	84.868	.795
90.093	1.995	89.907	.524
95.047	1.010	94.953	.274
100.000	.025	100.000	.025
L. E. radius: 0.994 percent c T. E. radius: 0.028 percent c			

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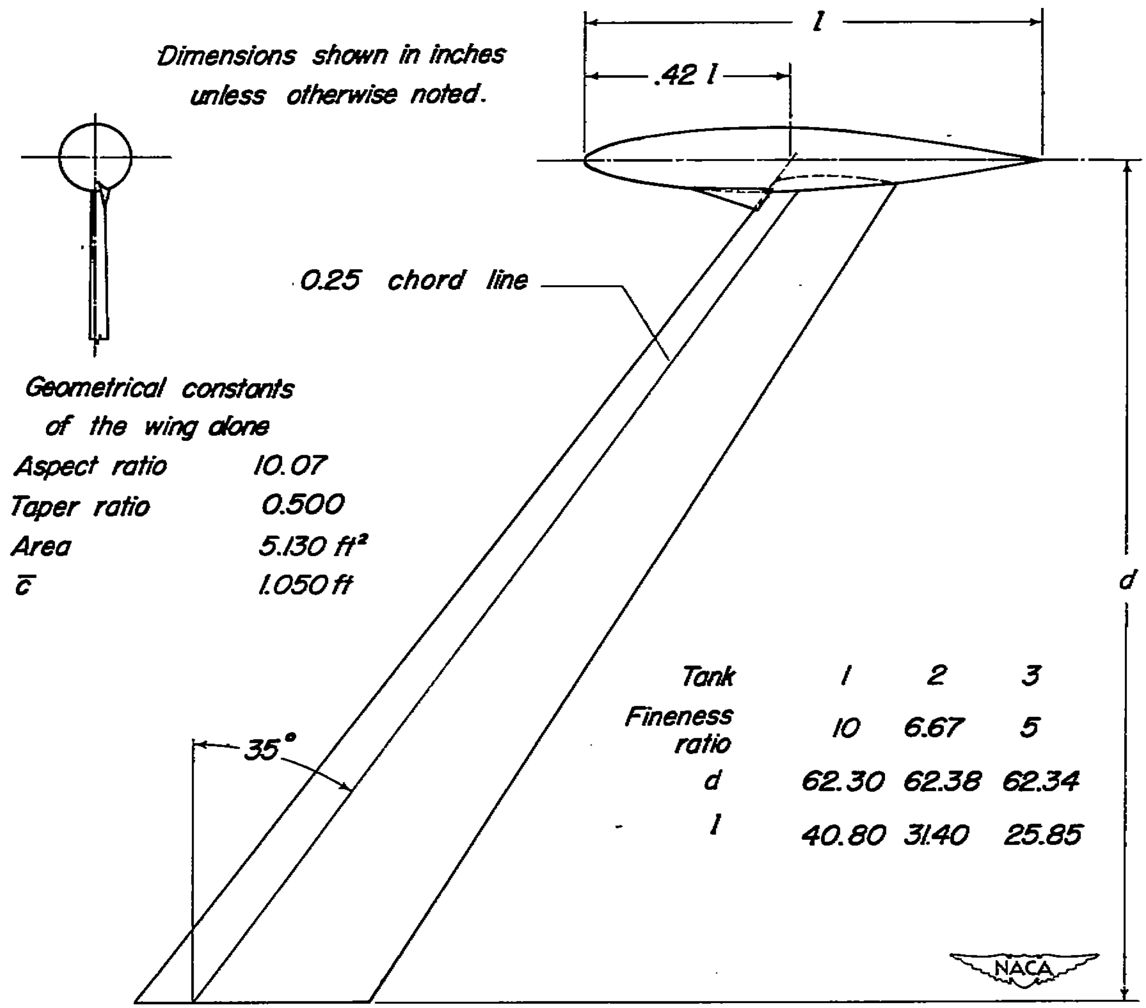
TABLE II

TIP-TANK COORDINATES

[Station and ordinates given in percent of tank length]

Fineness ratio 10 (NACA 65A010)		Fineness ratio 6.67 (NACA 65_2A015)		Fineness ratio 5 (NACA $65_{(215)}$A020)	
Station	Radius	Station	Radius	Station	Radius
0	0	0	0	0	0
.50	.765	.50	1.131	.50	1.508
.75	.928	.75	1.371	.75	1.828
1.25	1.183	1.25	1.750	1.25	2.333
2.50	1.623	2.50	2.412	2.50	3.216
5.00	2.182	5.00	3.255	5.00	4.340
7.50	2.650	7.50	3.962	7.50	5.283
10	3.040	10	4.553	10	6.071
15	3.658	15	5.488	15	7.317
20	4.127	20	6.198	20	8.264
25	4.483	25	6.734	25	8.979
30	4.742	30	7.122	30	9.496
35	4.912	35	7.376	35	9.835
40	4.995	40	7.496	40	9.995
45	4.983	45	7.467	45	9.956
50	4.863	50	7.269	50	9.692
55	4.632	55	6.903	55	9.204
60	4.304	60	6.393	60	8.524
65	3.899	65	5.772	65	7.696
70	3.432	70	5.063	70	6.751
75	2.912	75	4.282	75	5.709
80	2.352	80	3.451	80	4.601
85	1.771	85	2.598	85	3.464
90	1.188	90	1.743	90	2.324
95	.604	95	.887	95	1.183
100	.021	100	.032	100	.043

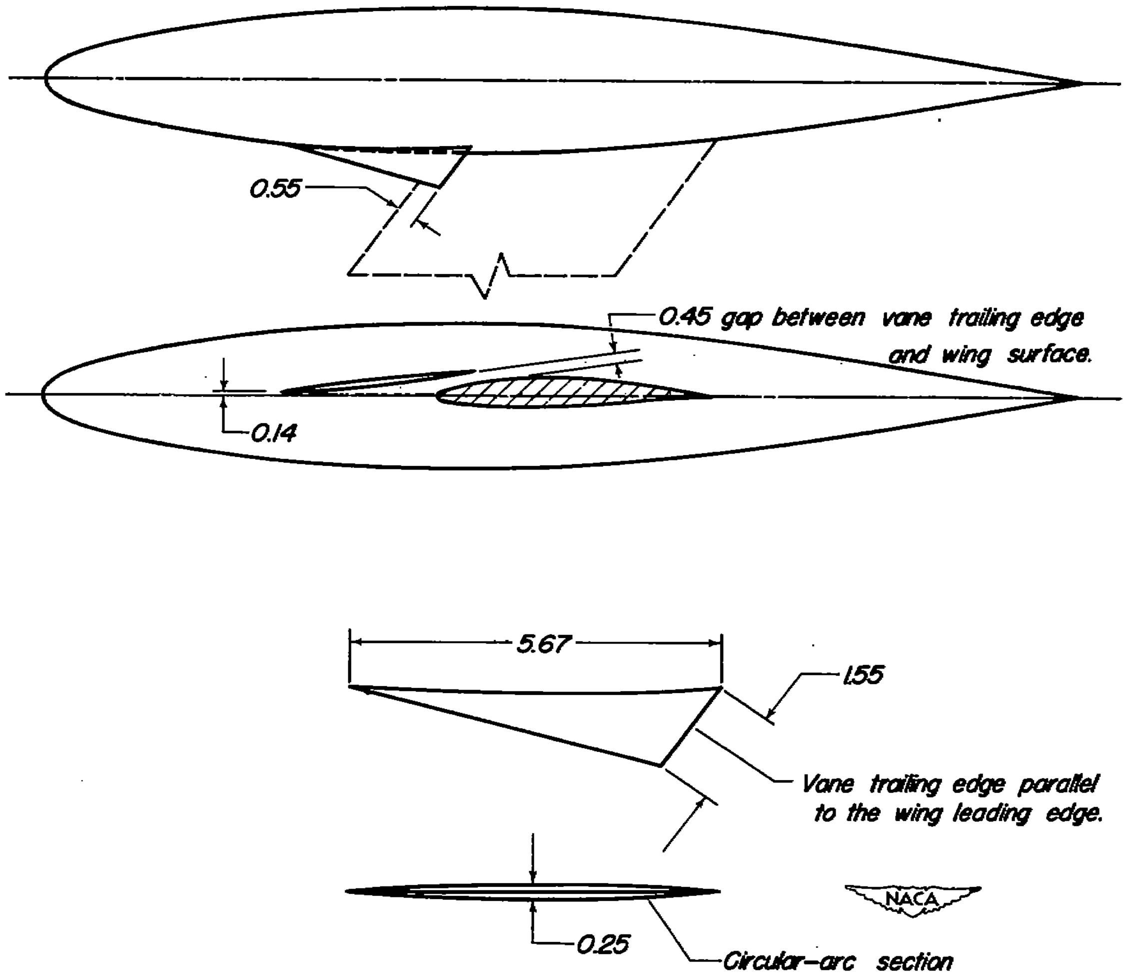
Nose radius, percent of tank length: Fineness ratio 10, 0.639; fineness ratio 6.67, 1.446; fineness ratio 5, 2.571.



Airfoil section and tip-tank coordinates are given in tables I and II.

(a) Wing and tank assembly.

Figure 1.– Geometry of the models.



Detail of vane

(b) Tip-tank and vane details.

Figure 1.– Concluded.

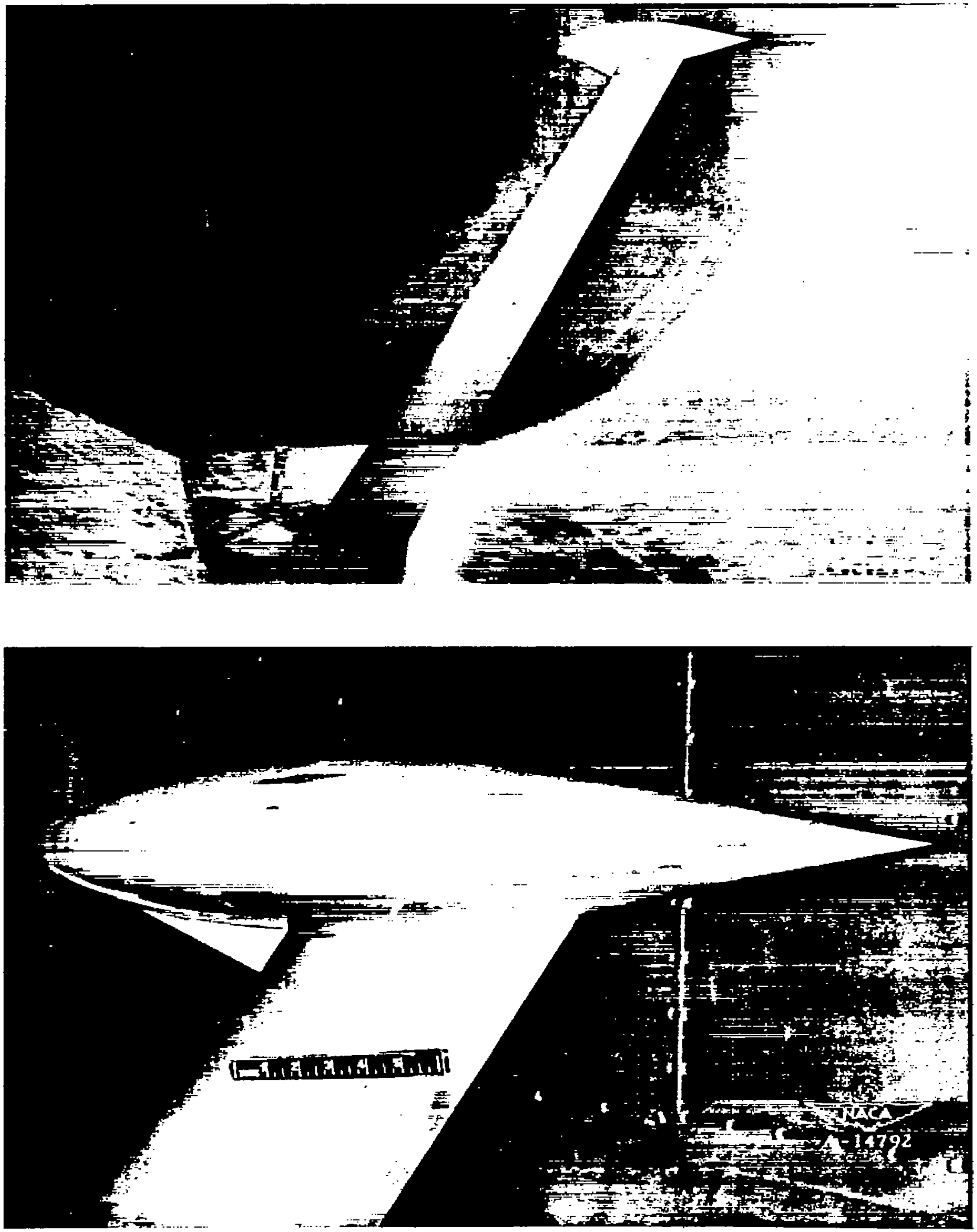
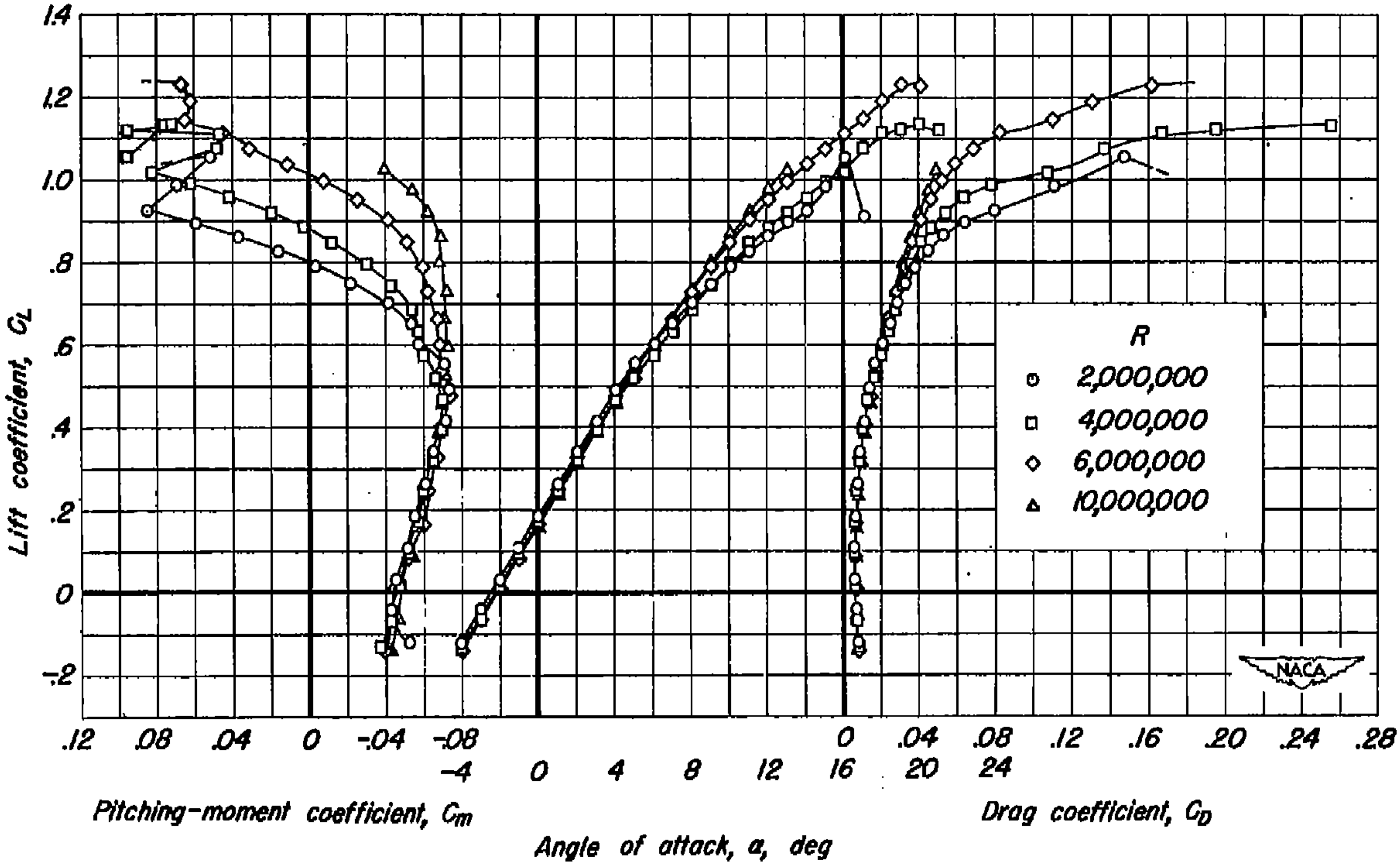


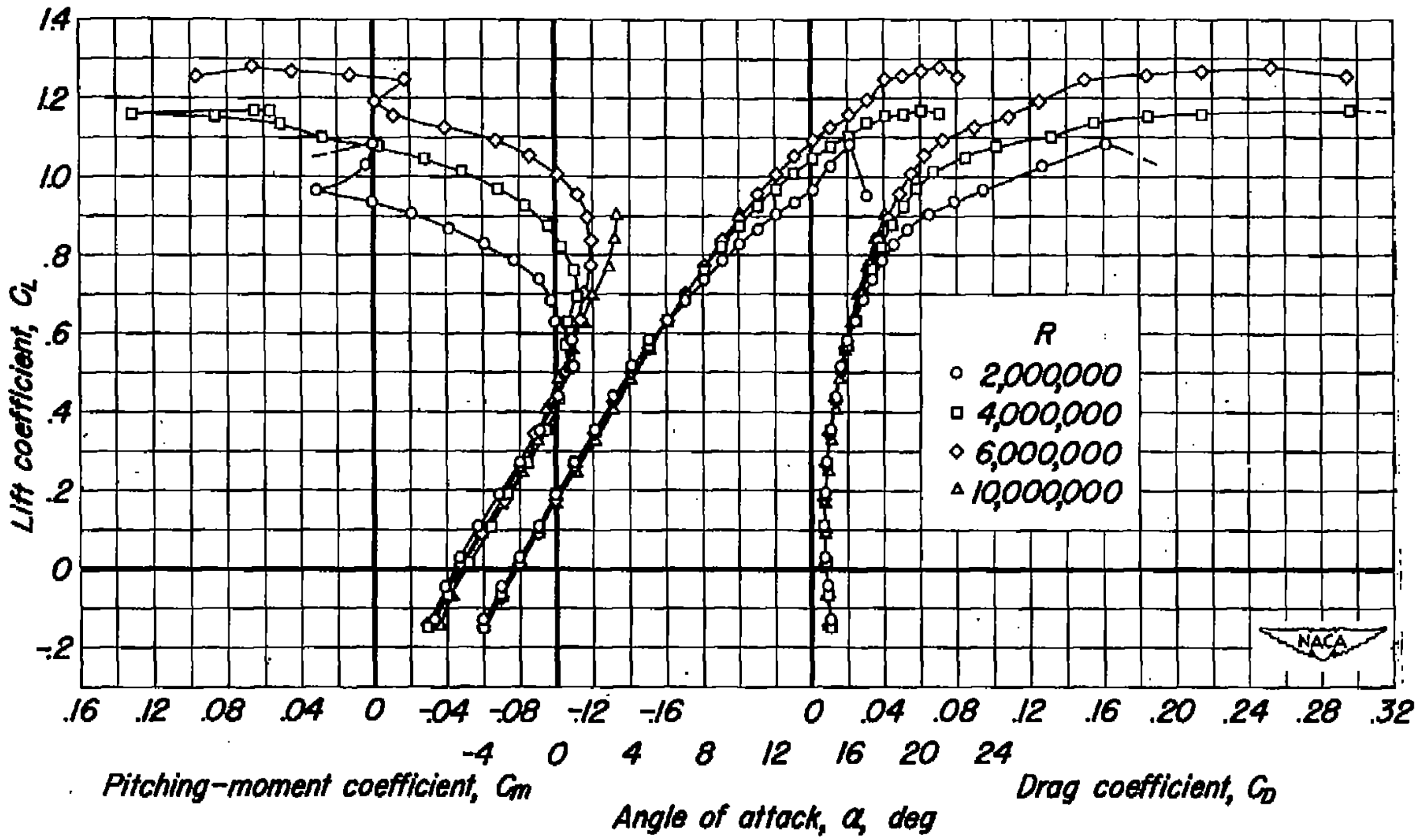
Figure 2.— Photographs of the model mounted in the Ames 12-foot pressure wind tunnel and the tip-tank installation.



(a) Wing alone.

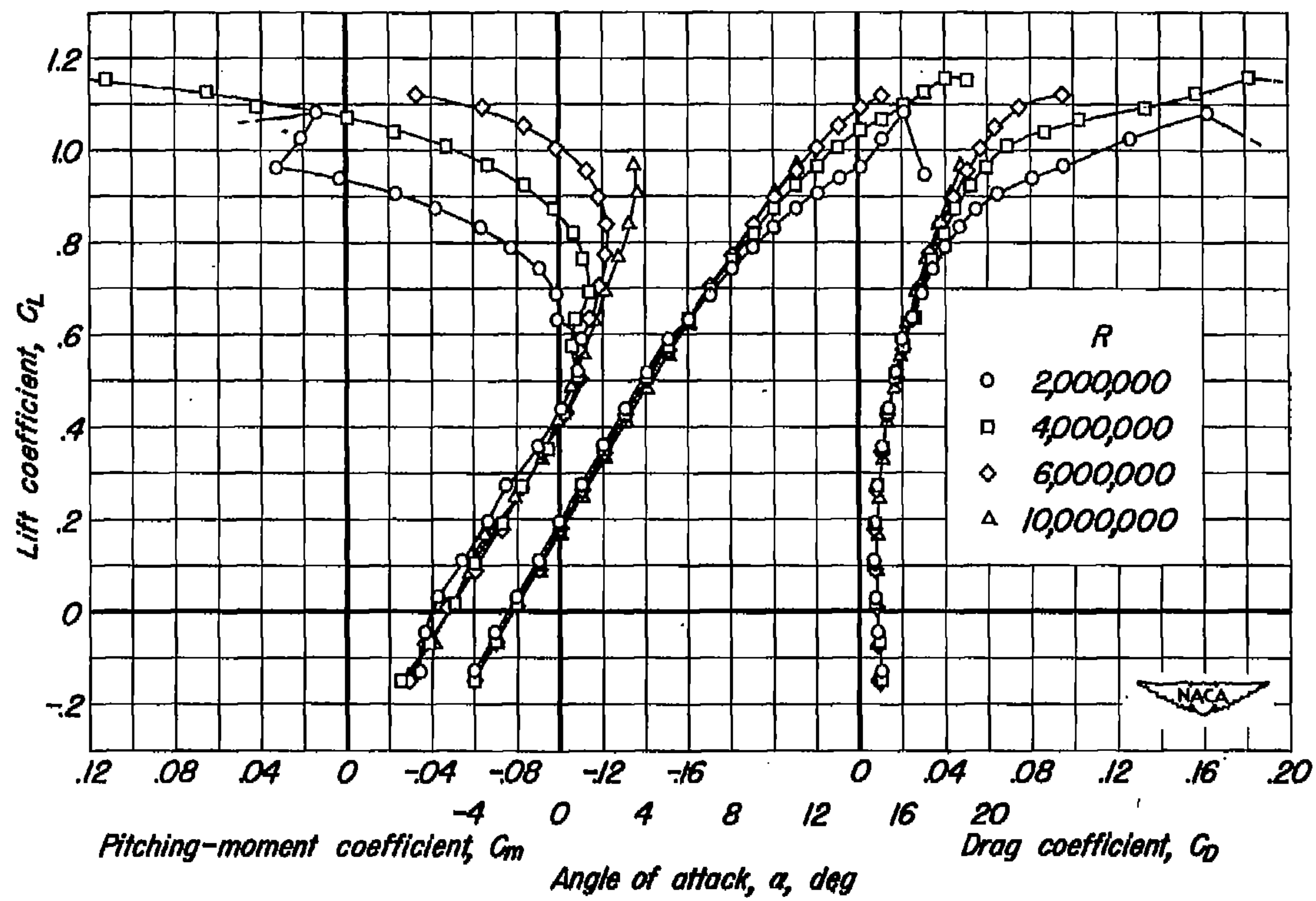
Figure 3.- The effect of Reynolds number on the low-speed aerodynamic characteristics. M, 0.25.

[redacted]



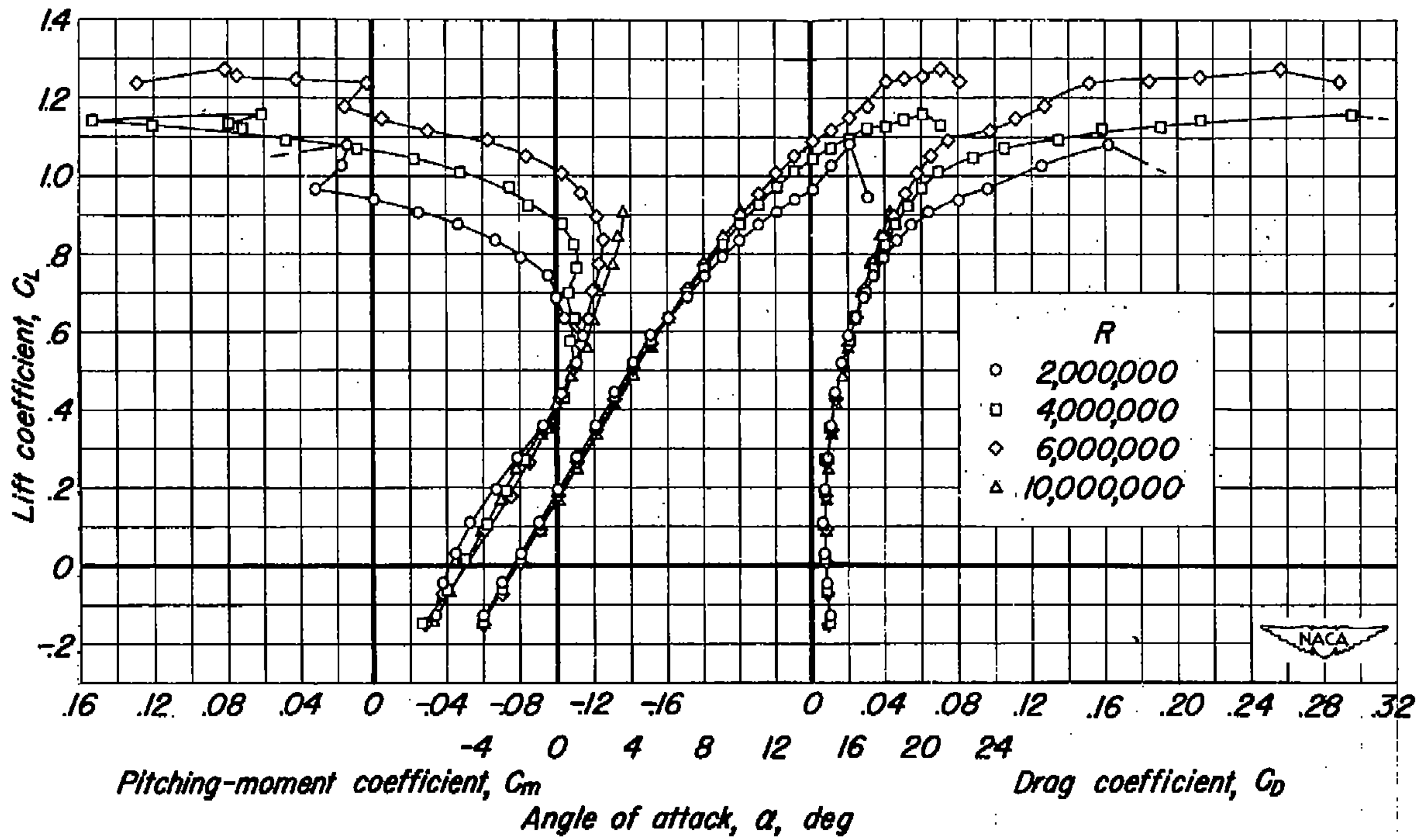
(b) Wing and tip tank of fineness ratio 10.

Figure 3.- Continued.



(c) Wing and tip tank of fineness ratio 6.67.

Figure 3.- Continued.



(d) Wing and tip tank of fineness ratio 5.

Figure 3.- Concluded.

[redacted]

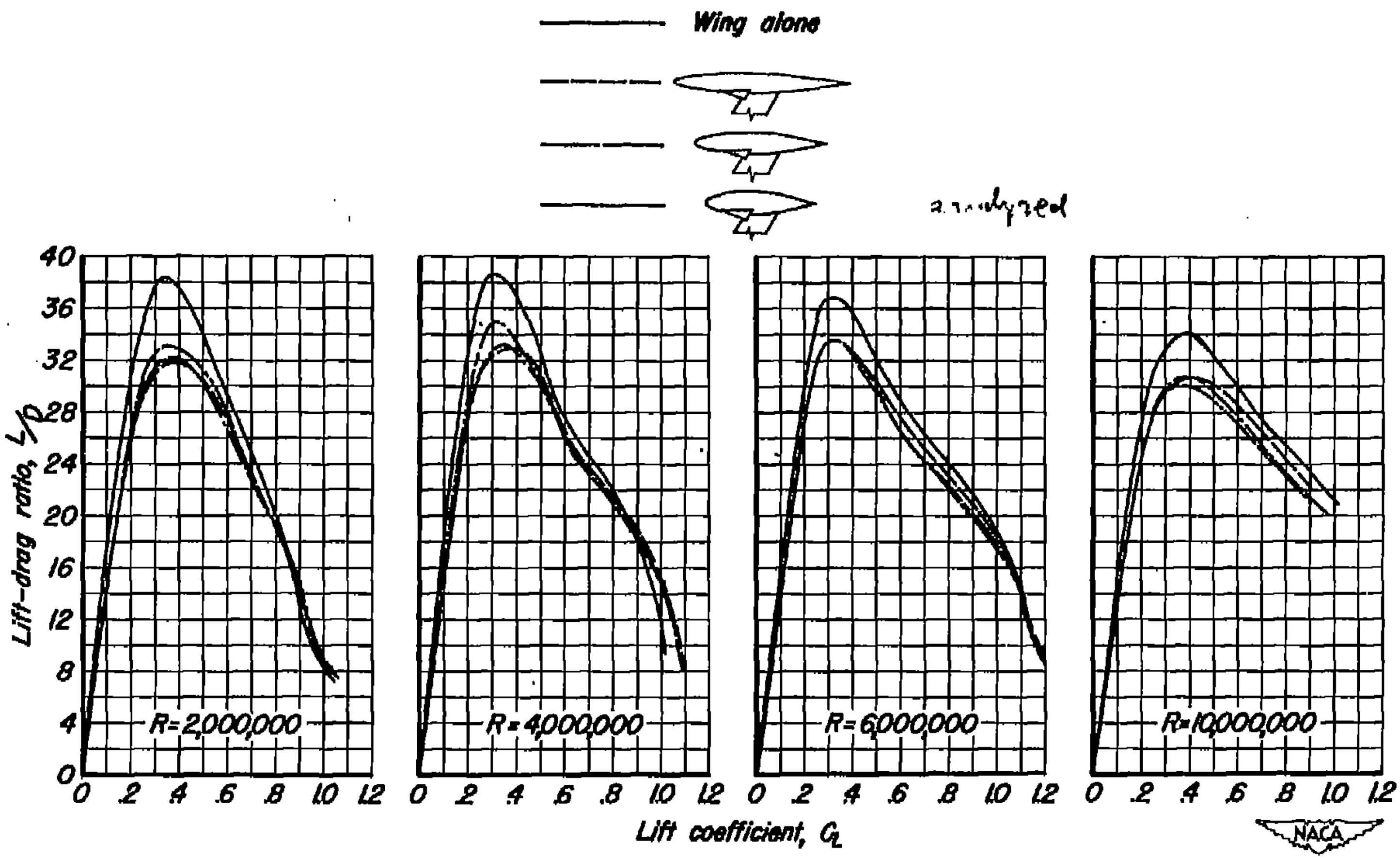


Figure 4.– The effect of Reynolds number on the lift-drag ratio at low speed. M, 0.25.

[redacted]

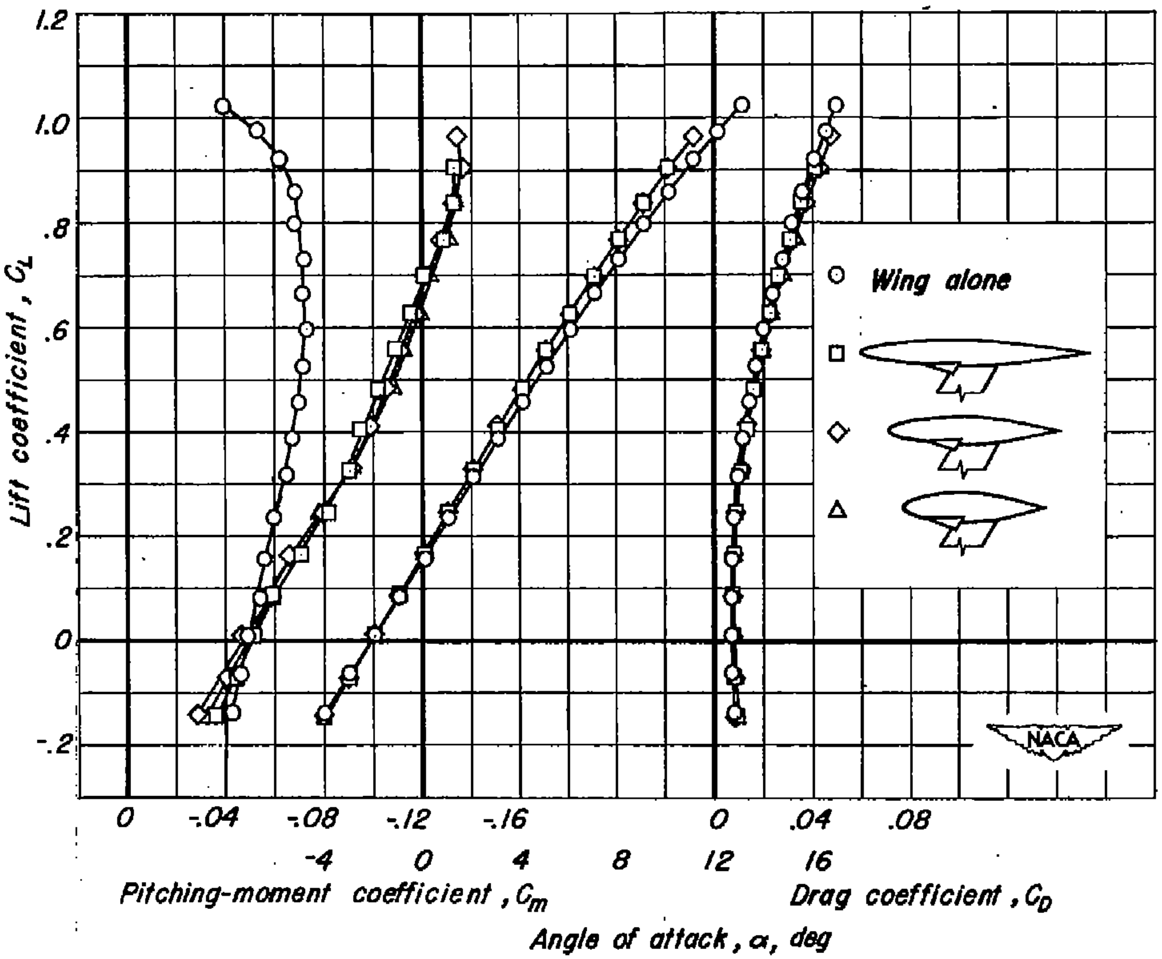


Figure 5.– The effect of tip tanks on the low-speed aerodynamic characteristics. R, 10,000,000; M, 0.25.

[redacted]

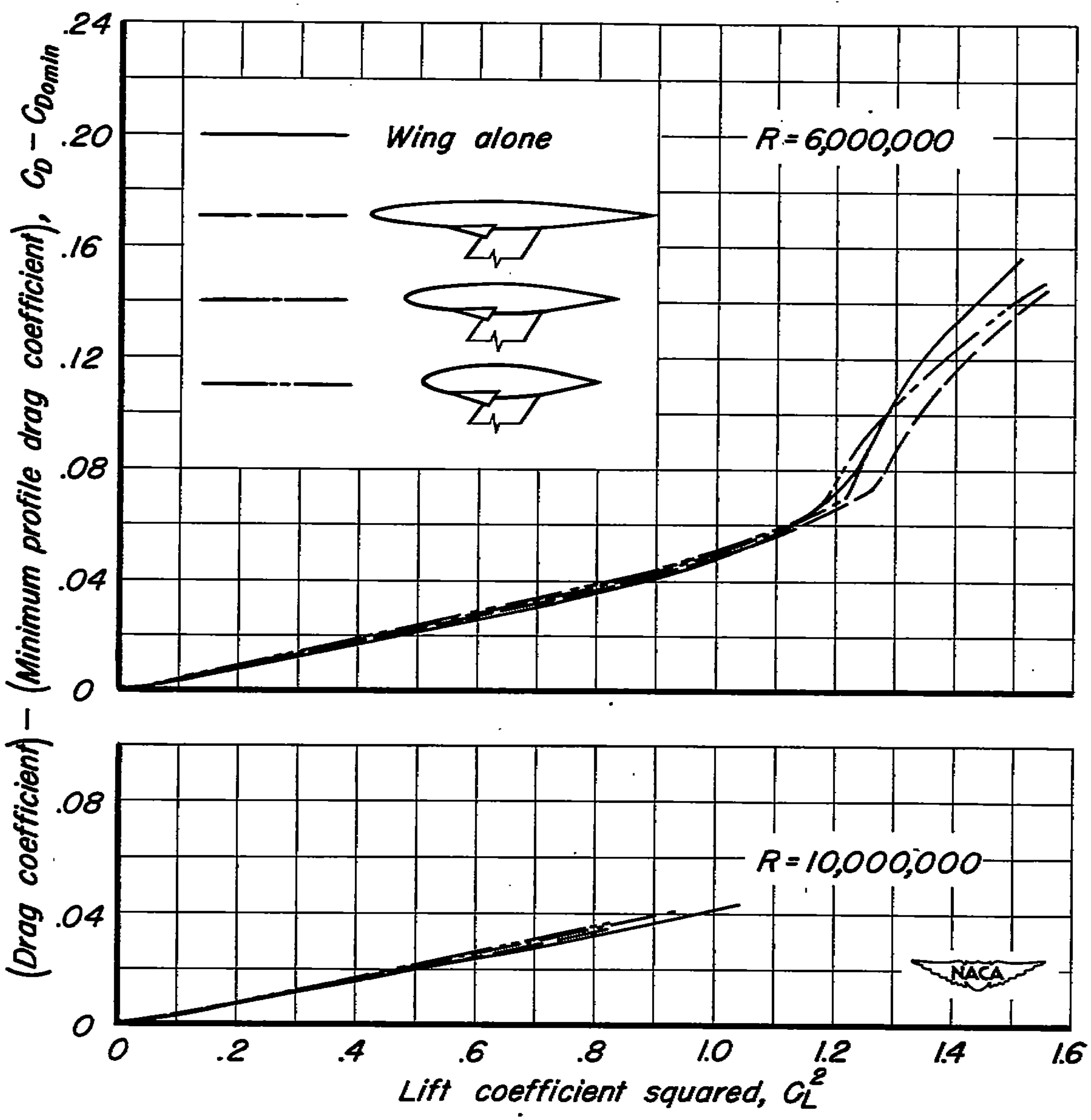
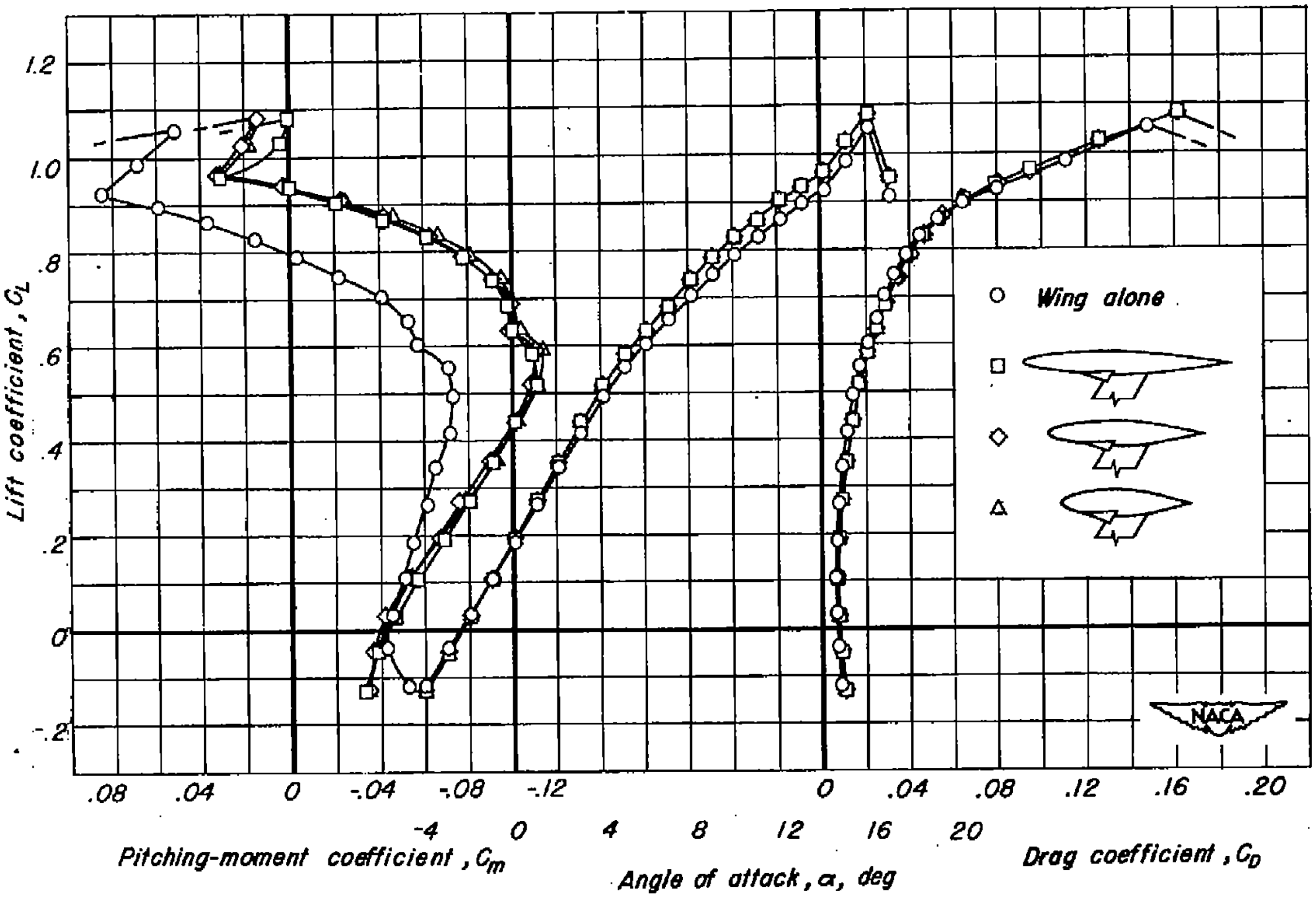


Figure 6.– The variation of drag coefficient minus the minimum profile drag coefficient with lift coefficient squared. M, 0.25.

[redacted]

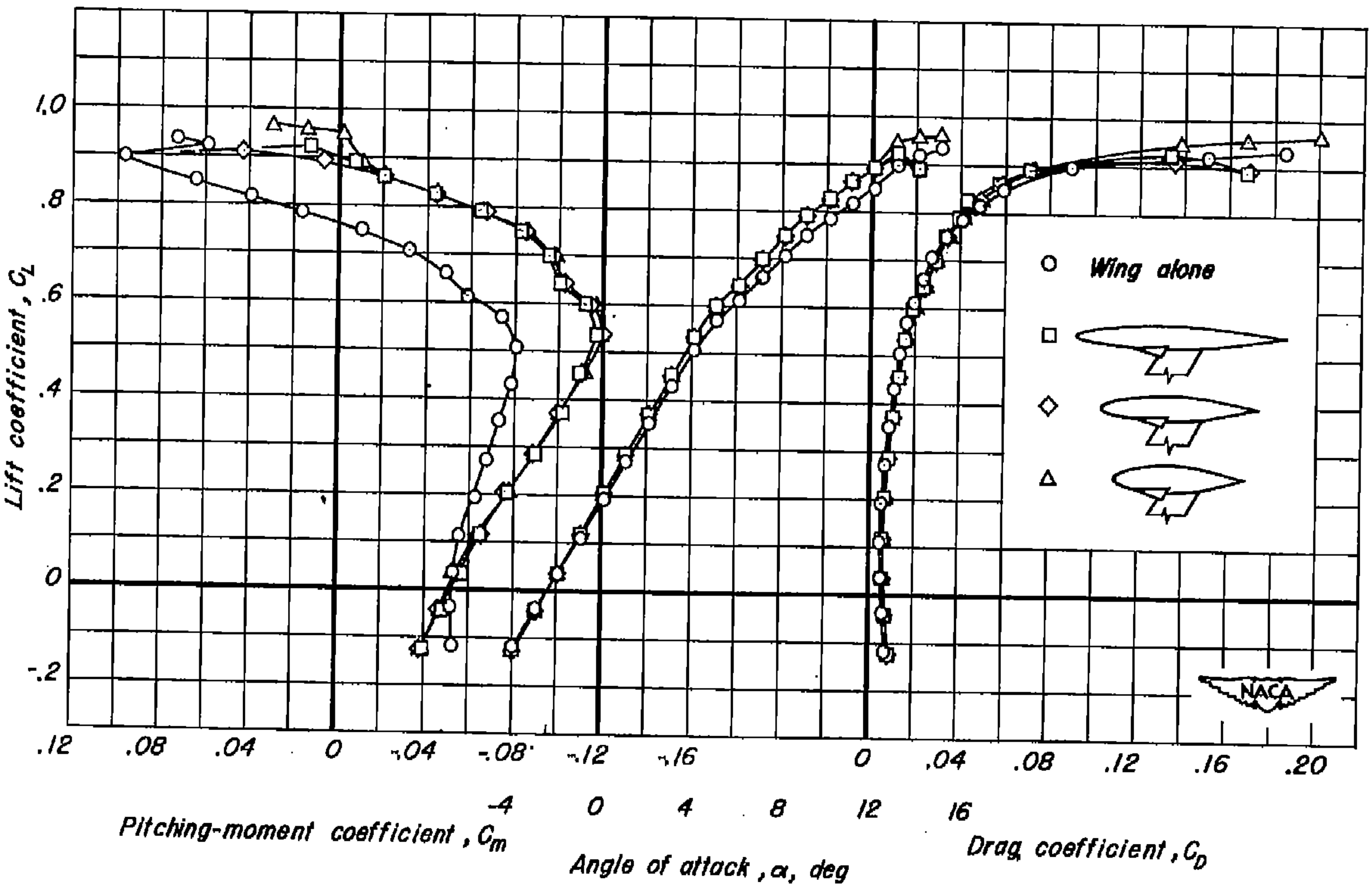


(a) M, 0.25.

Figure 7.– The effect of tip tanks on the aerodynamic characteristics. R, 2,000,000.

[redacted]

[redacted]

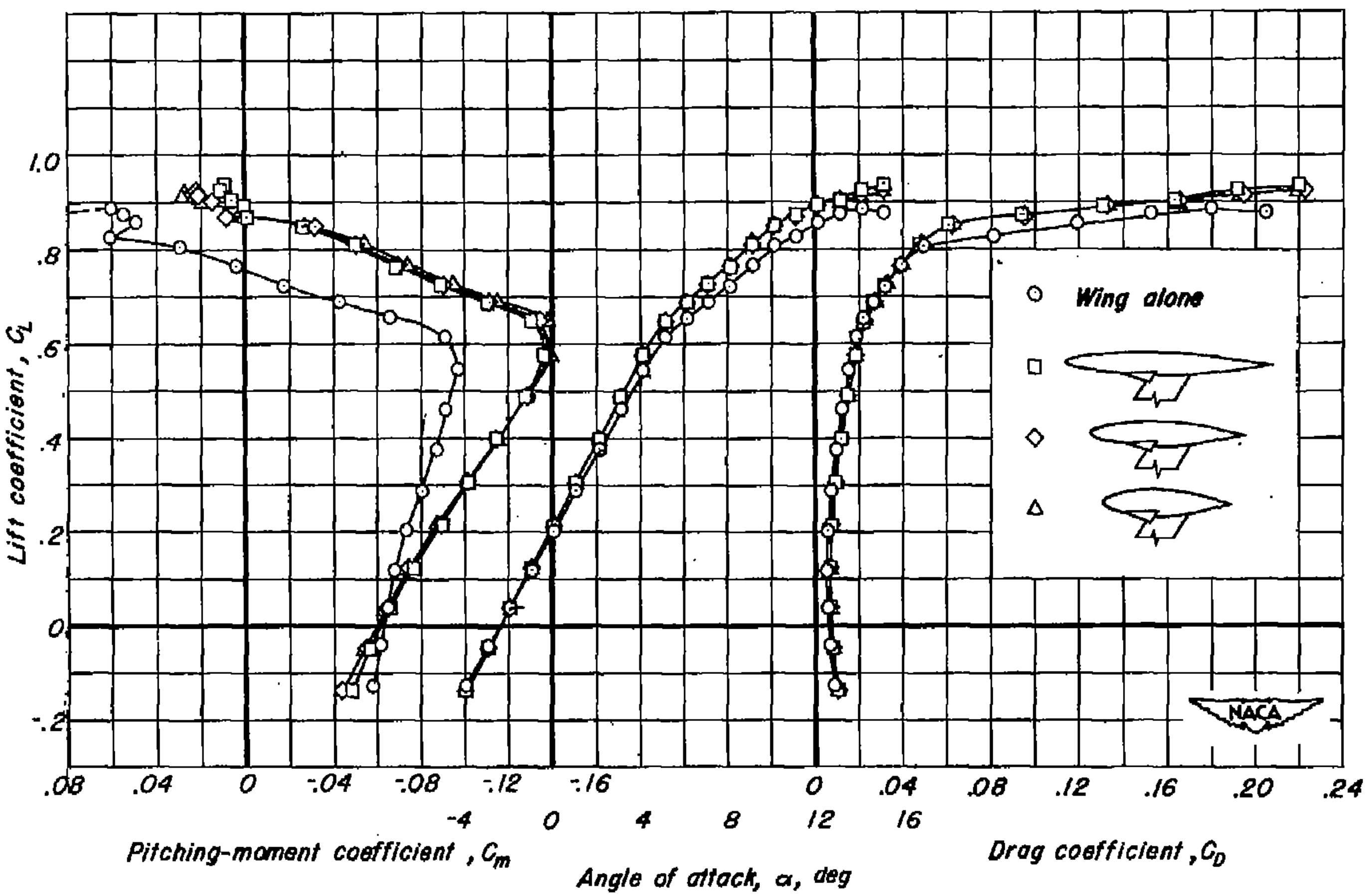


[redacted]

(b) M, 0.40.

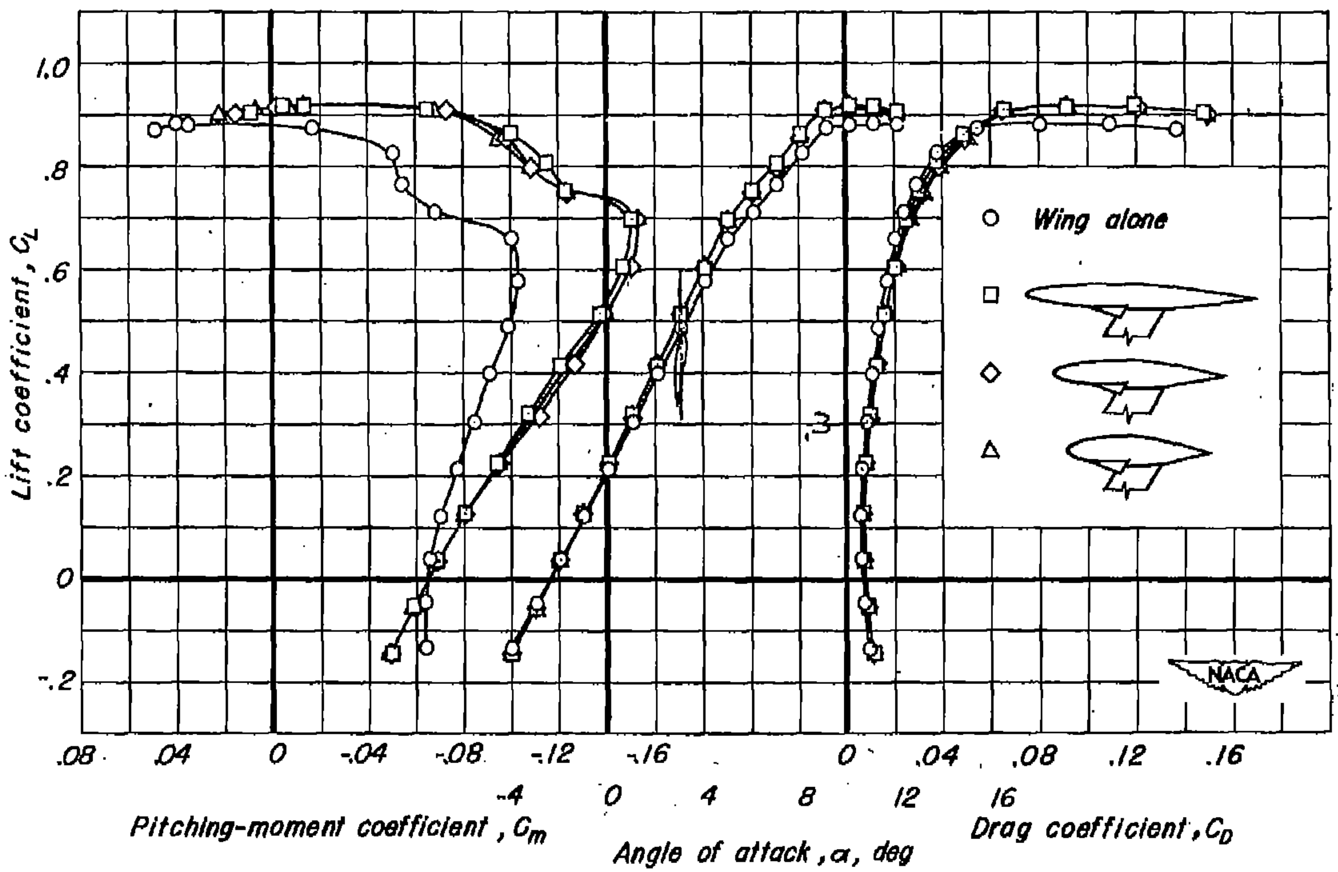
Figure 7— Continued.

[redacted]



(c) M, 0.60.

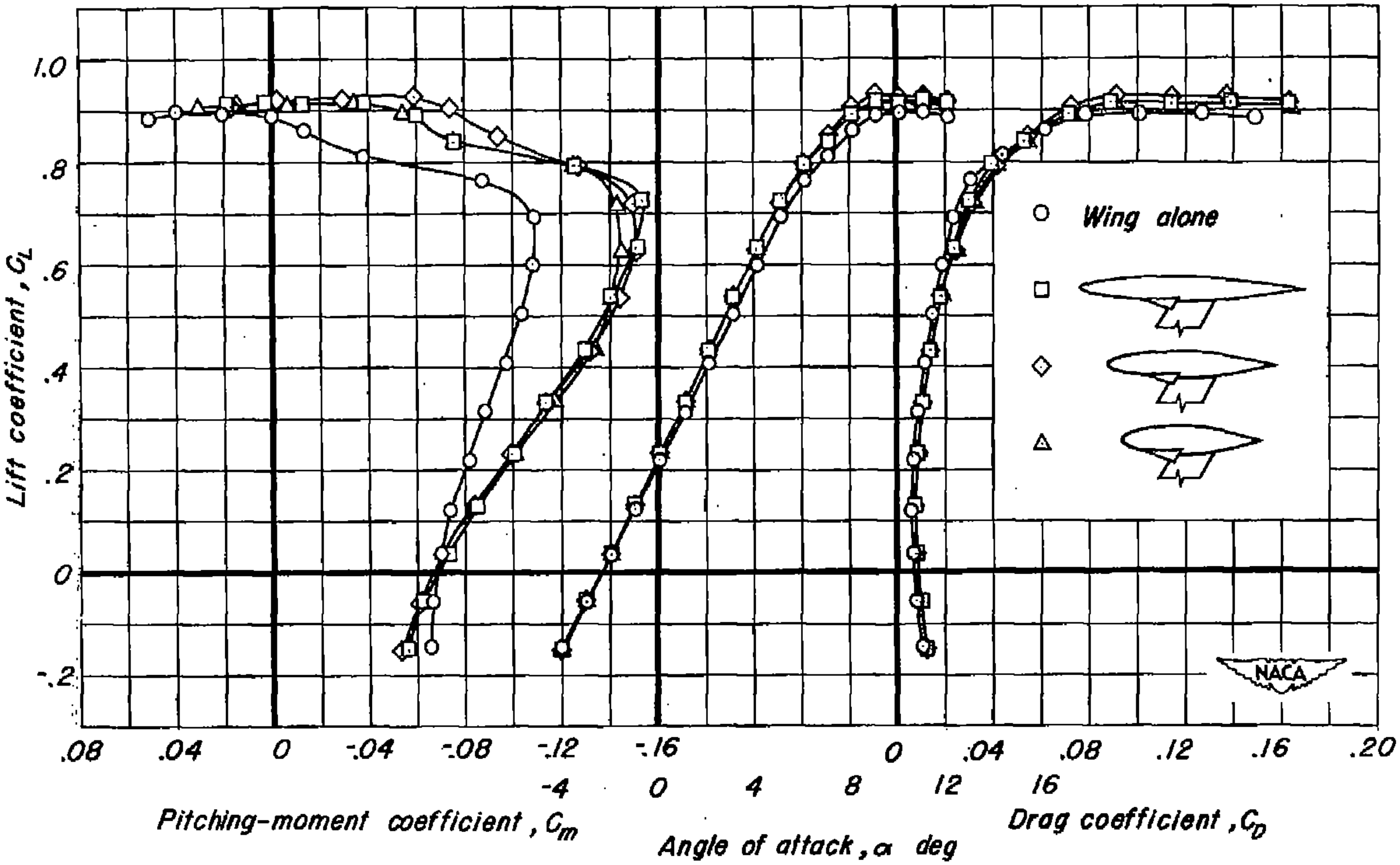
Figure 7– Continued.



(d) M, 0.70.

Figure 7– Continued.

[redacted]



(e) M, 0.75.

Figure 7— Continued.

[redacted]

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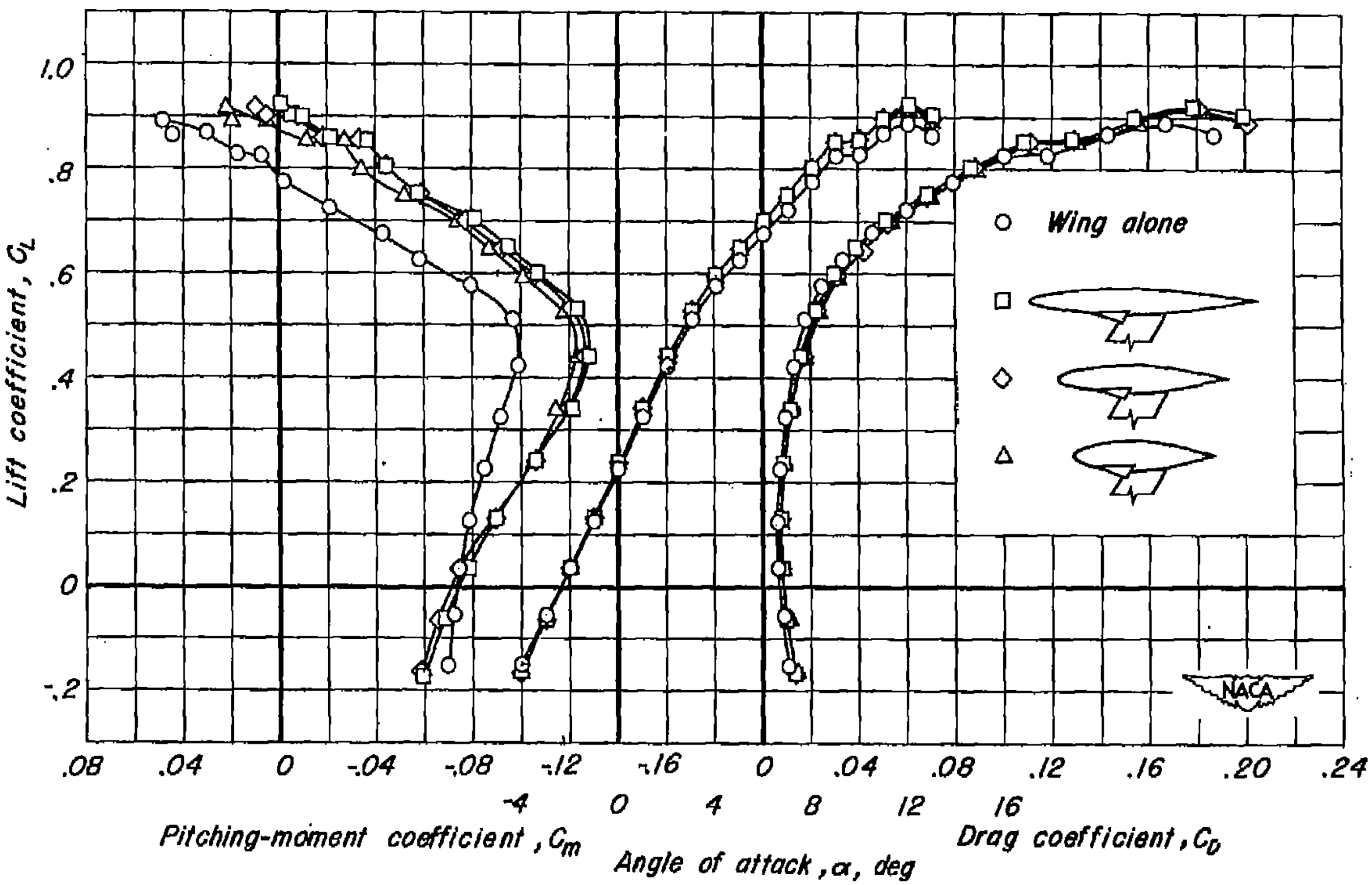

(f) M, 0.80.

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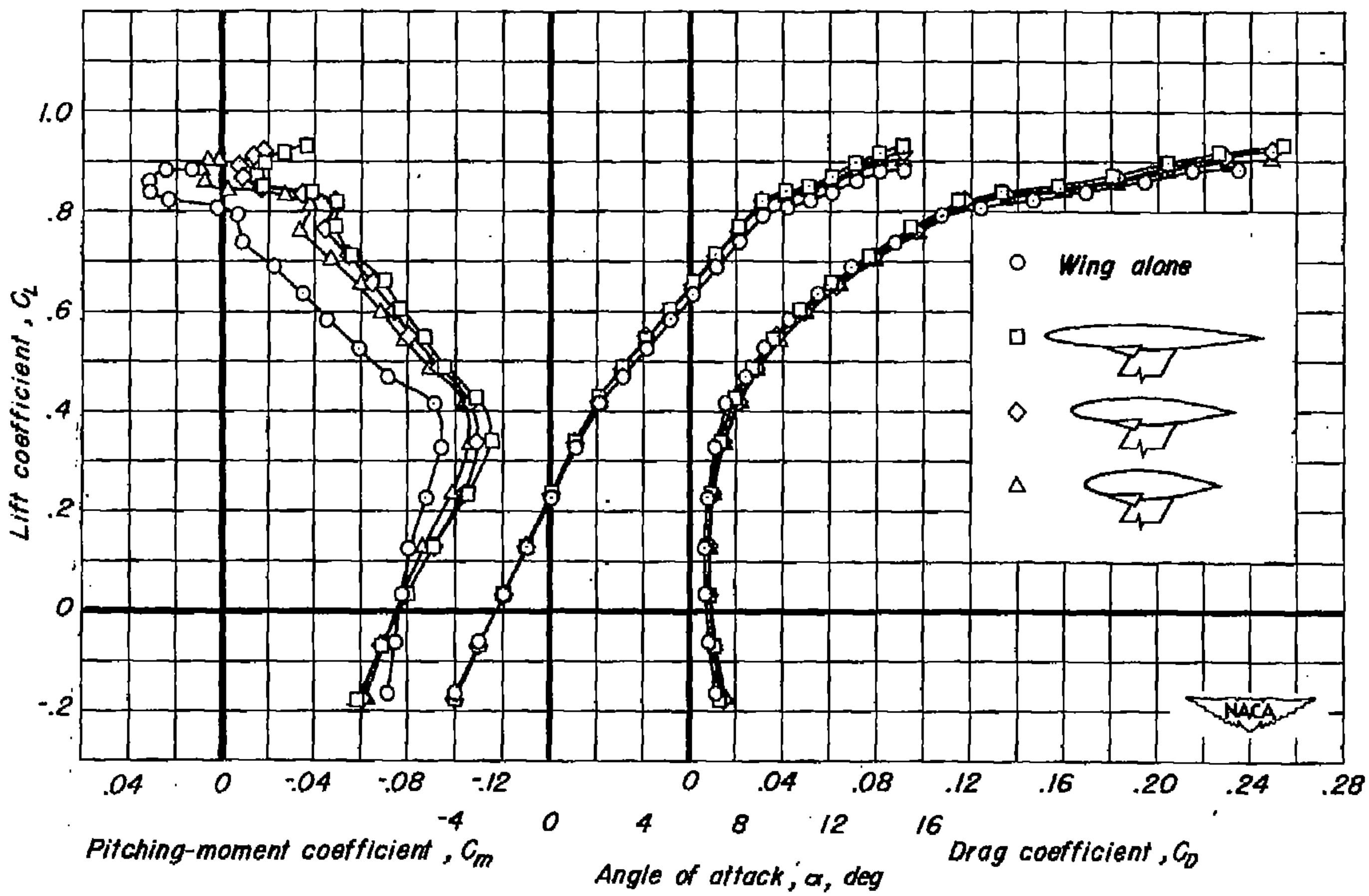
Figure 7.— Continued.



(g) M, 0.825.

Figure 7.— Continued.

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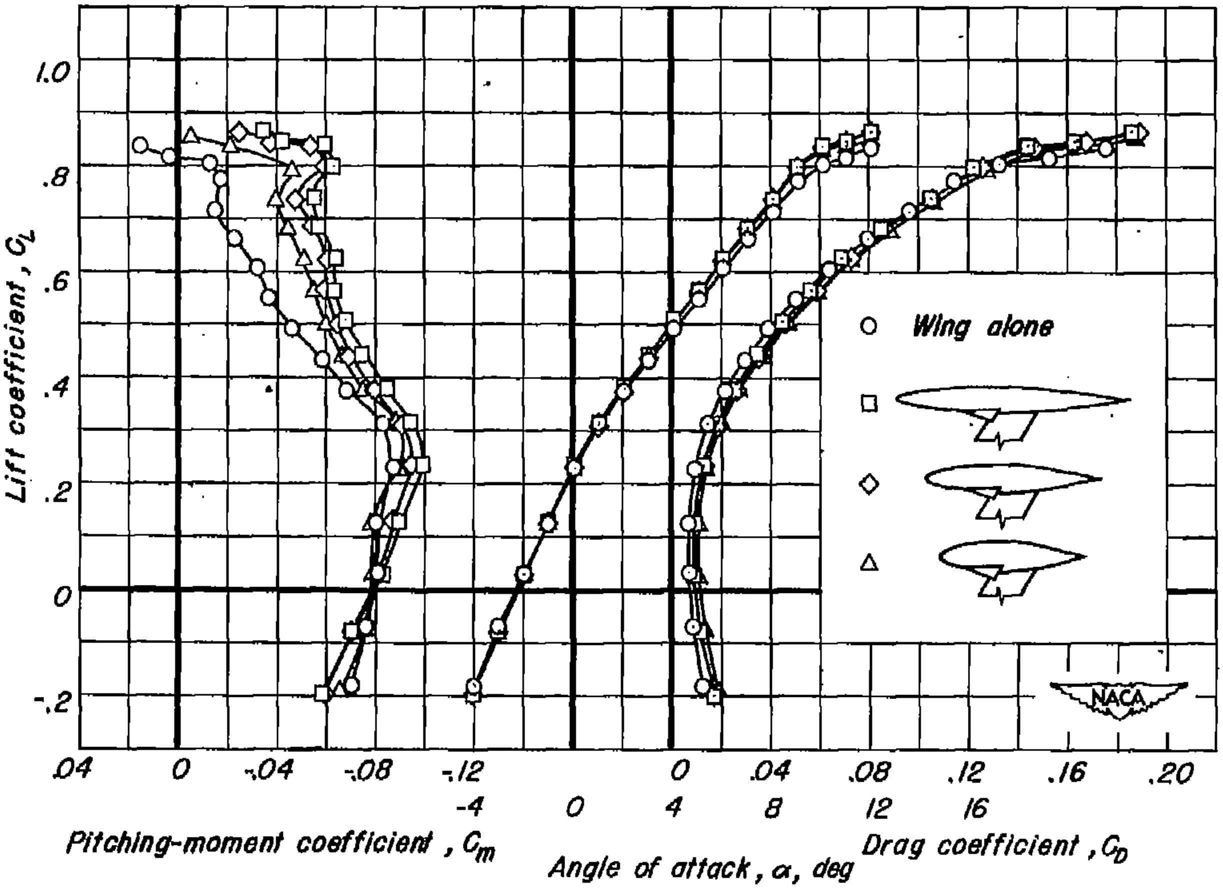

(h) M, 0.85.

Figure 7—Continued.

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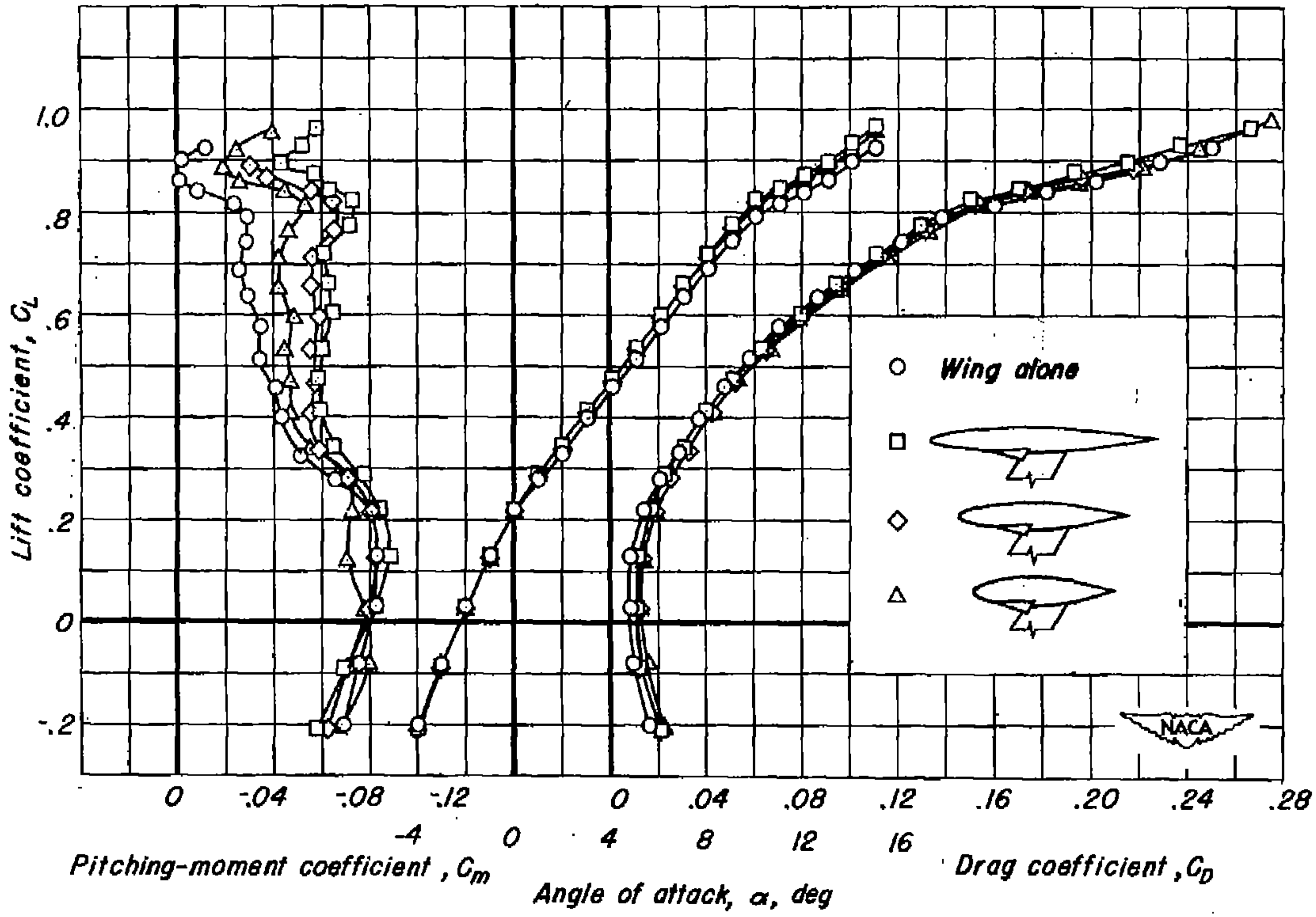

(i) M, 0.875.

Figure 7.- Continued.

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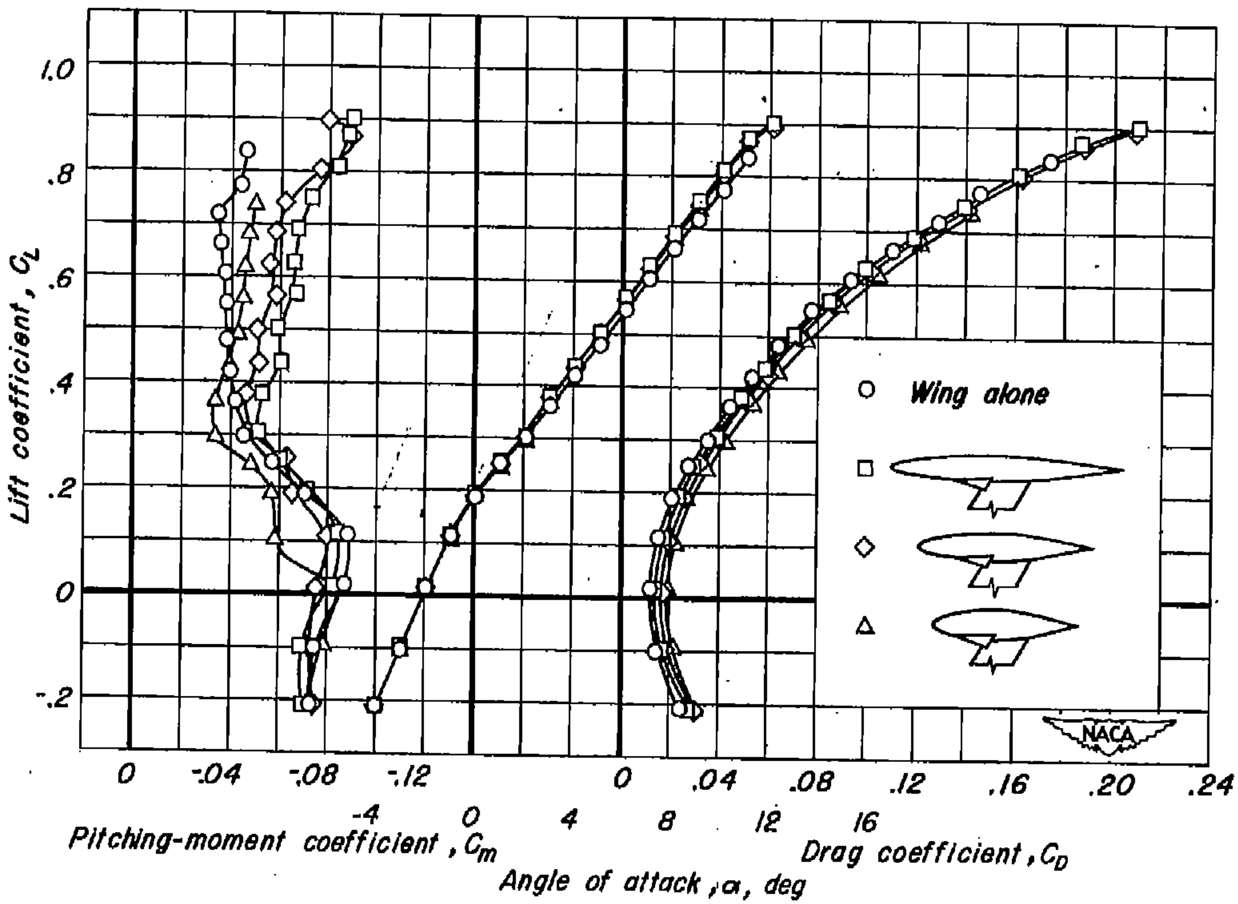


(j) M, 0.90.

Figure 7– Concluded.

[redacted]

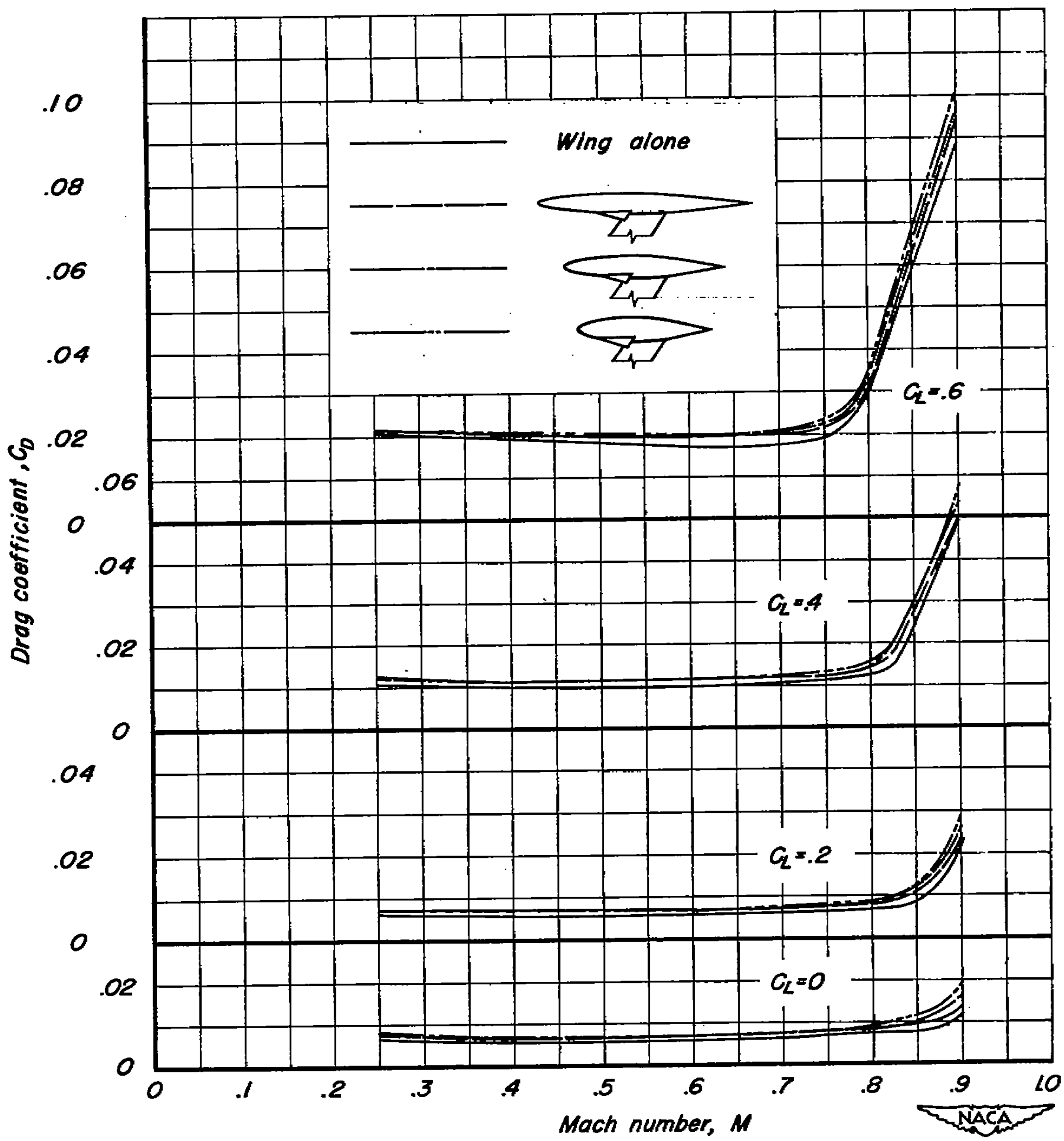
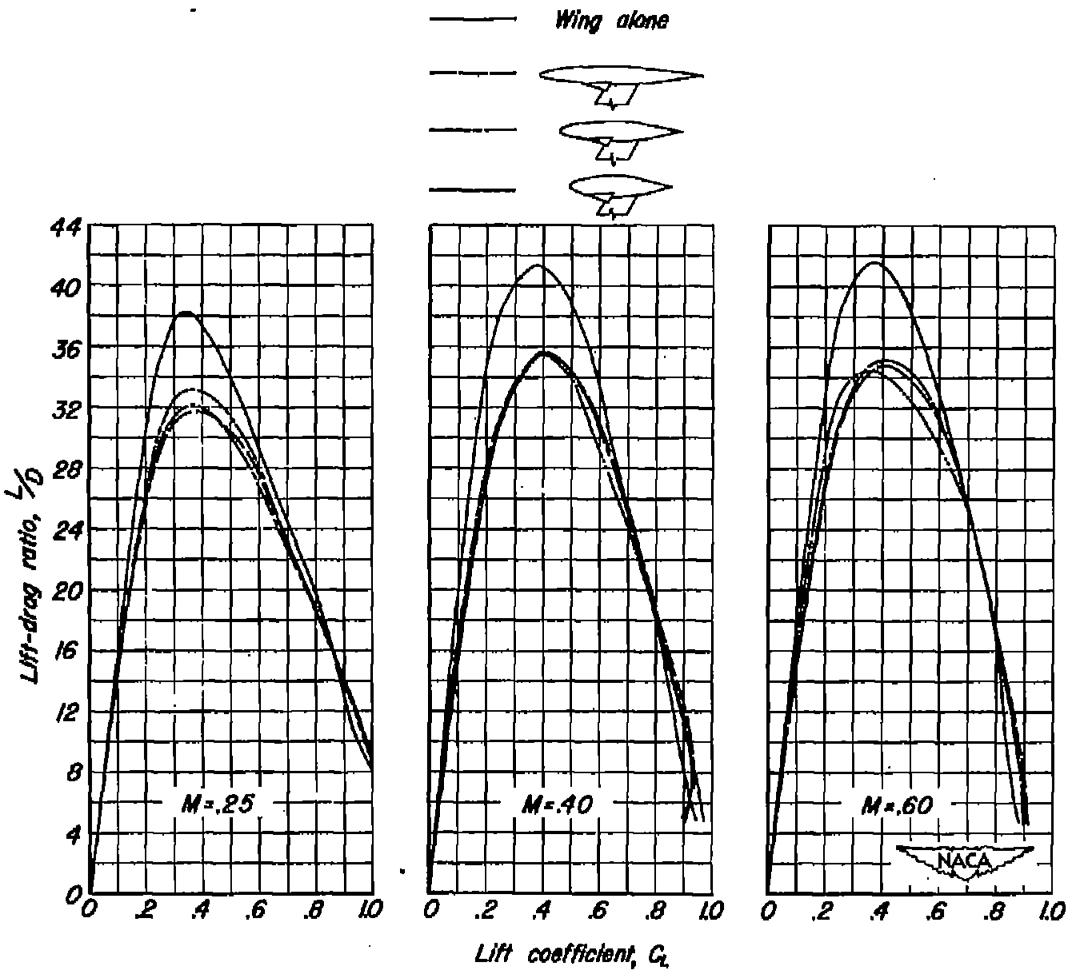


Figure 8.– The variation of drag coefficient with Mach number. R, 2,000,000.

[redacted]



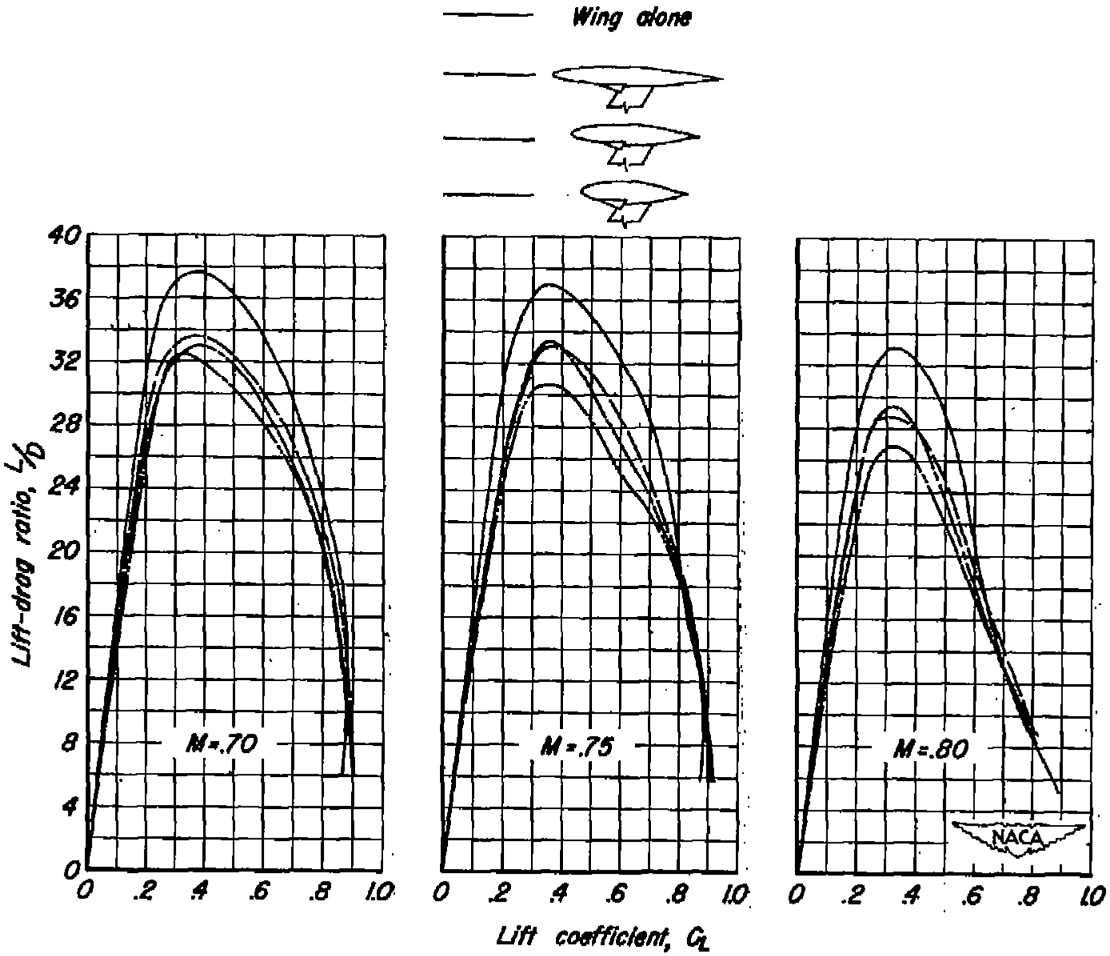
(a) M, 0.25 to 0.60.

AF22

Figure 9.- The effect of tip tanks on the lift-drag ratio. R, 2,000,000.

[redacted]

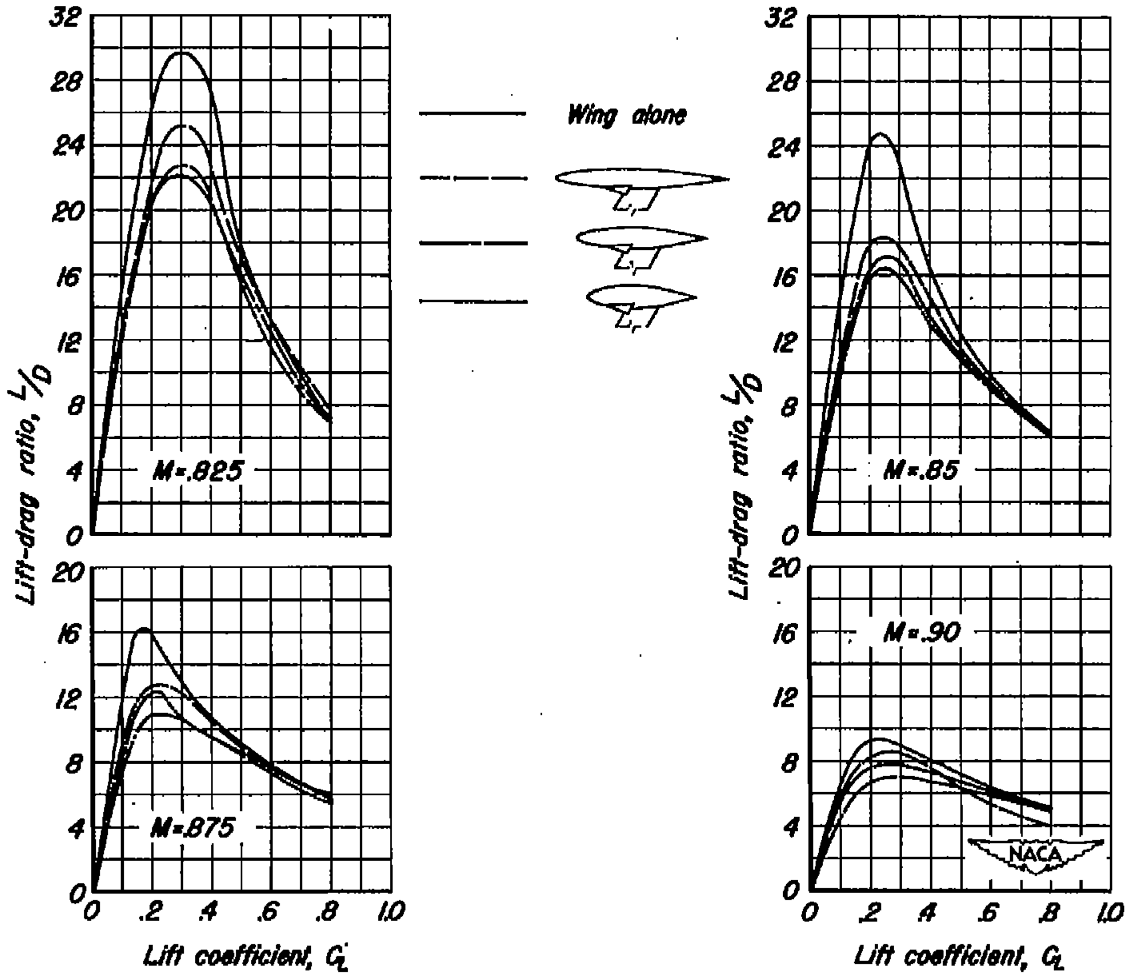
[redacted]



(b) M, 0.70 to 0.80.

Figure 9.- Continued.

[redacted]



(c) M, 0.825 to 0.90.

Figure 9.- Concluded.

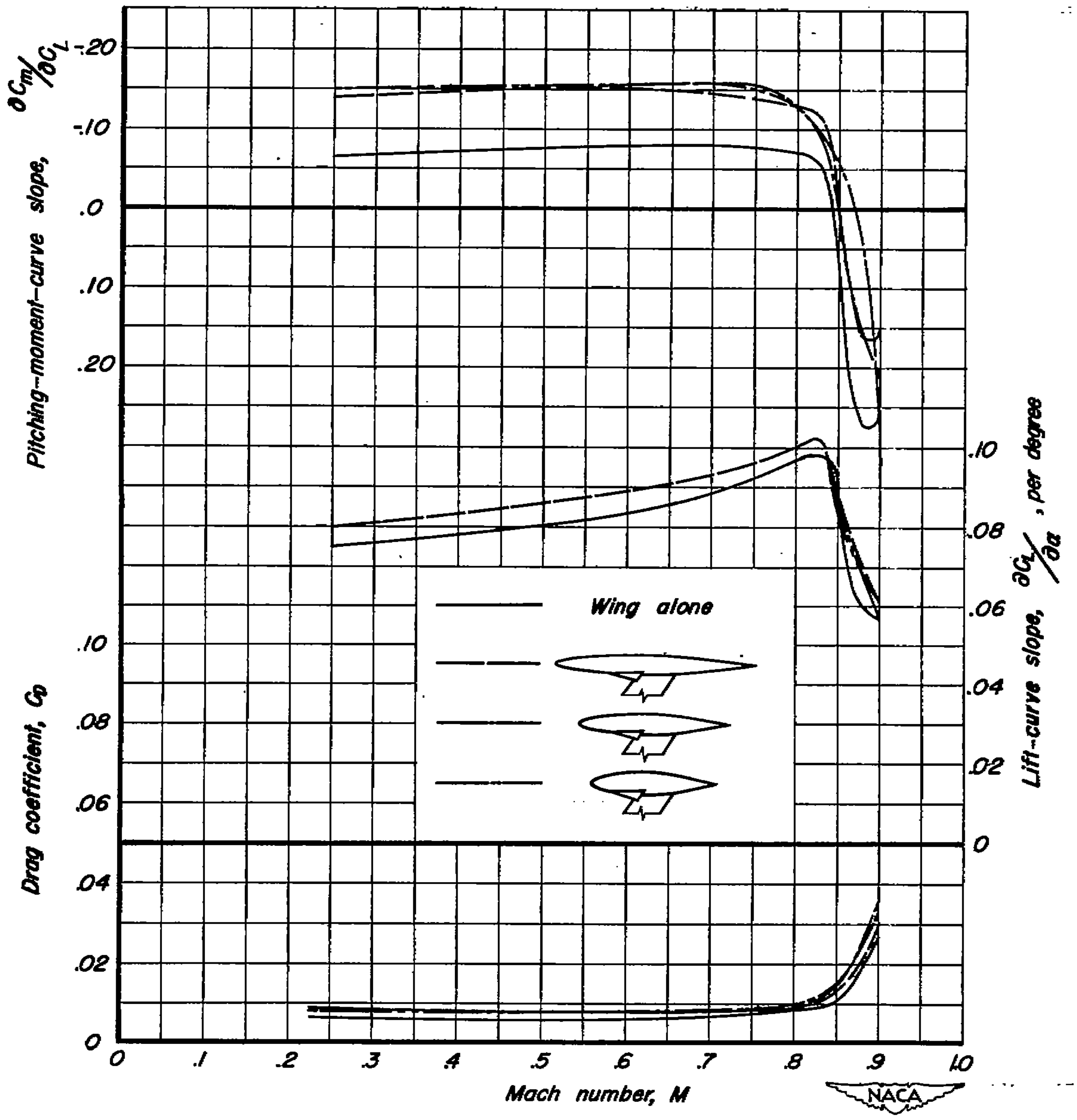


Figure 10.- The variations of pitching-moment-curve slope, lift-curve slope, and drag coefficient with Mach number. C_L, 0.25.

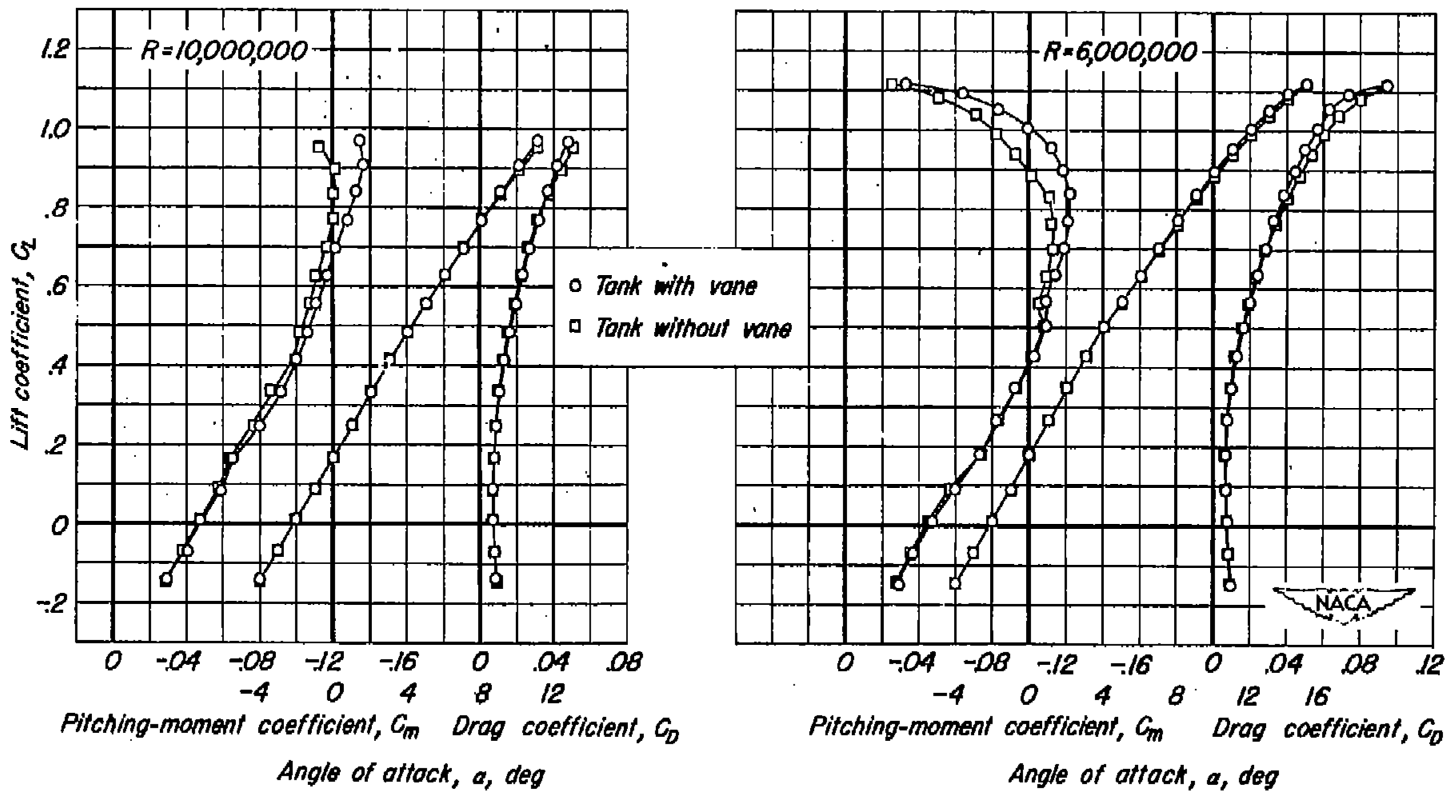
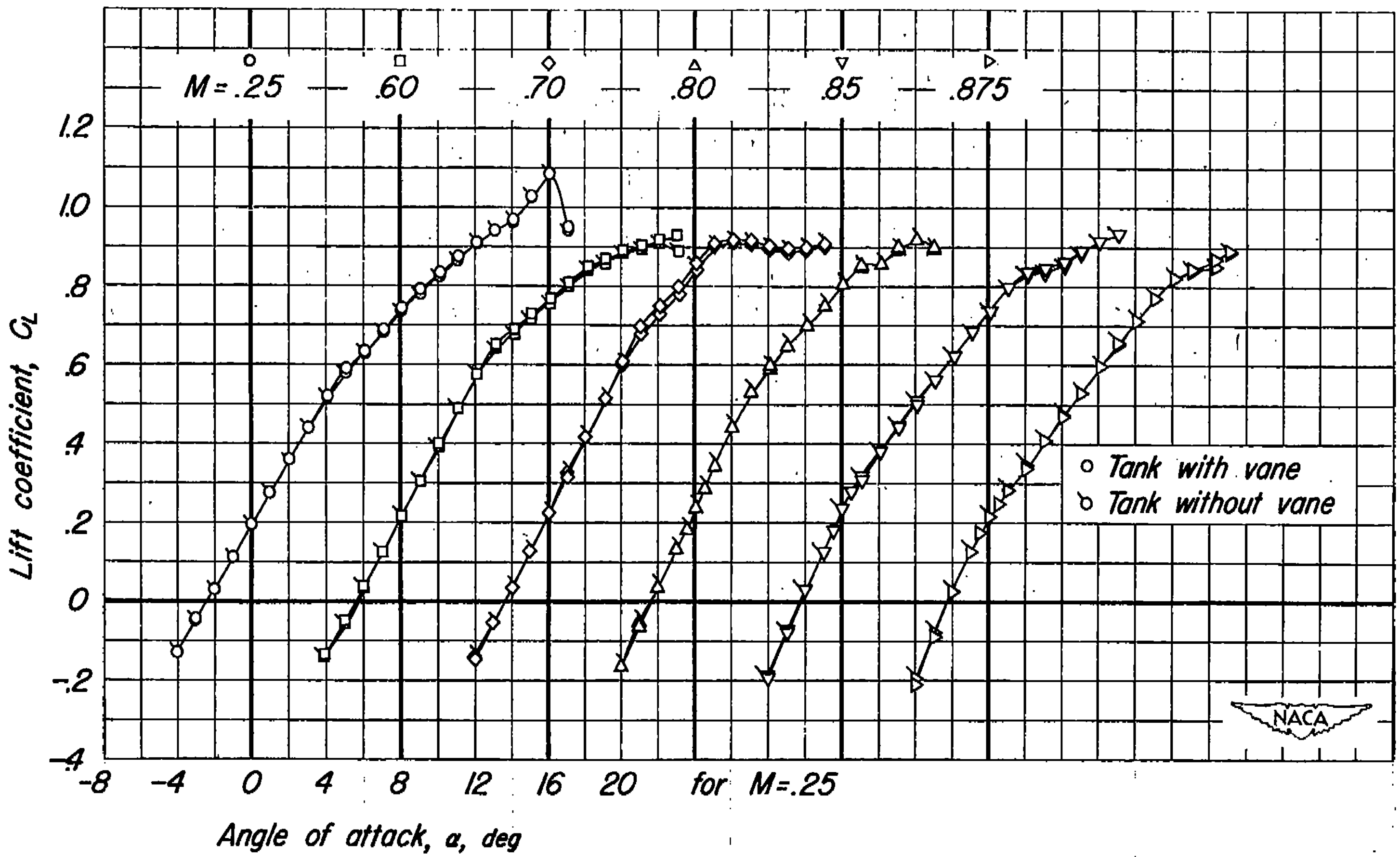


Figure 11.- The effect of the tip-tank vane on the low-speed aerodynamic characteristics of a wing with a tip tank of fineness ratio 6.67. M, 0.25.

[redacted]

[redacted]

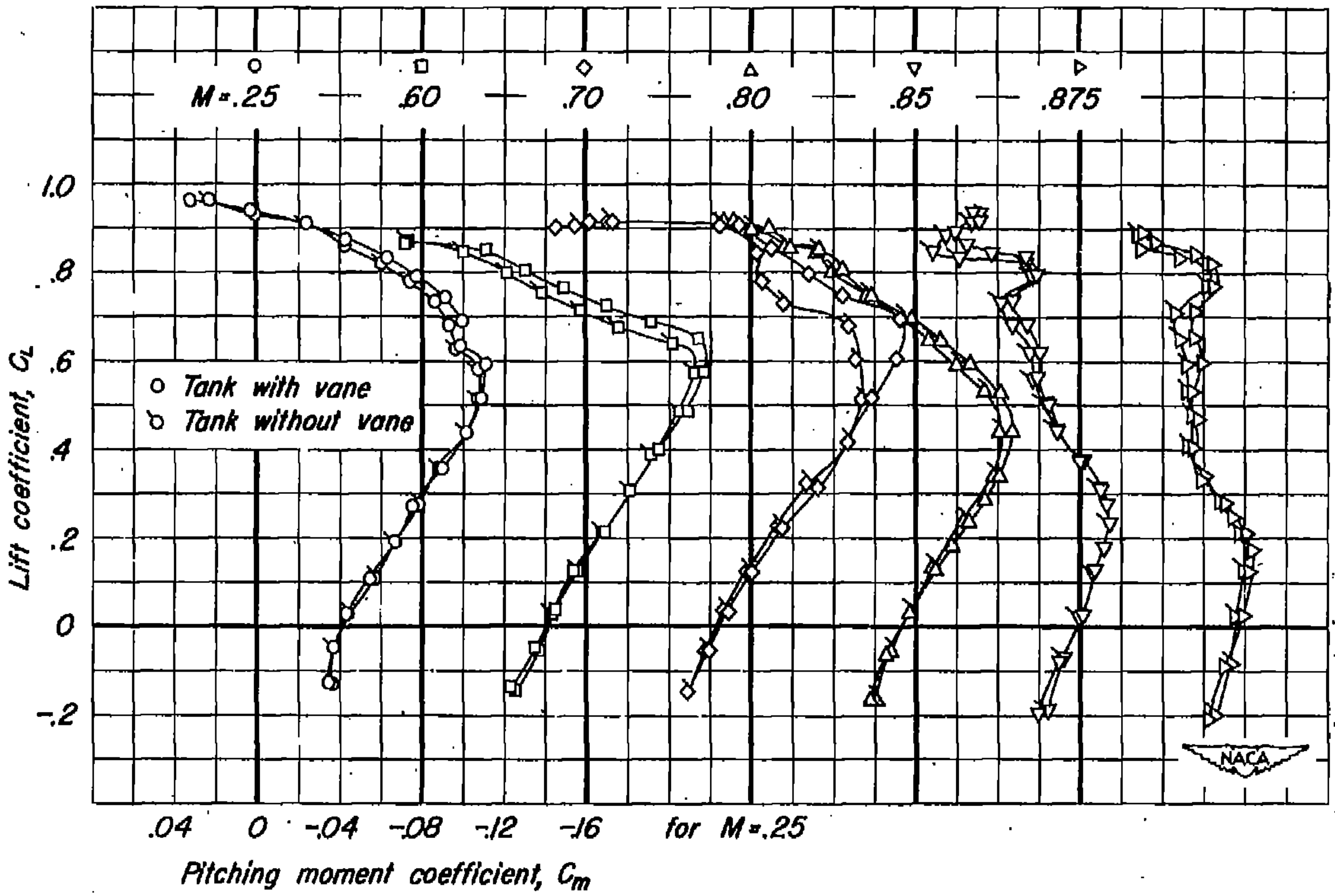


[redacted]

(a) C_L vs α.

Figure 12.- The effect of the tip-tank vane on the aerodynamic characteristics of a wing with a tip tank of fineness ratio 6.67. R, 2,000,000.

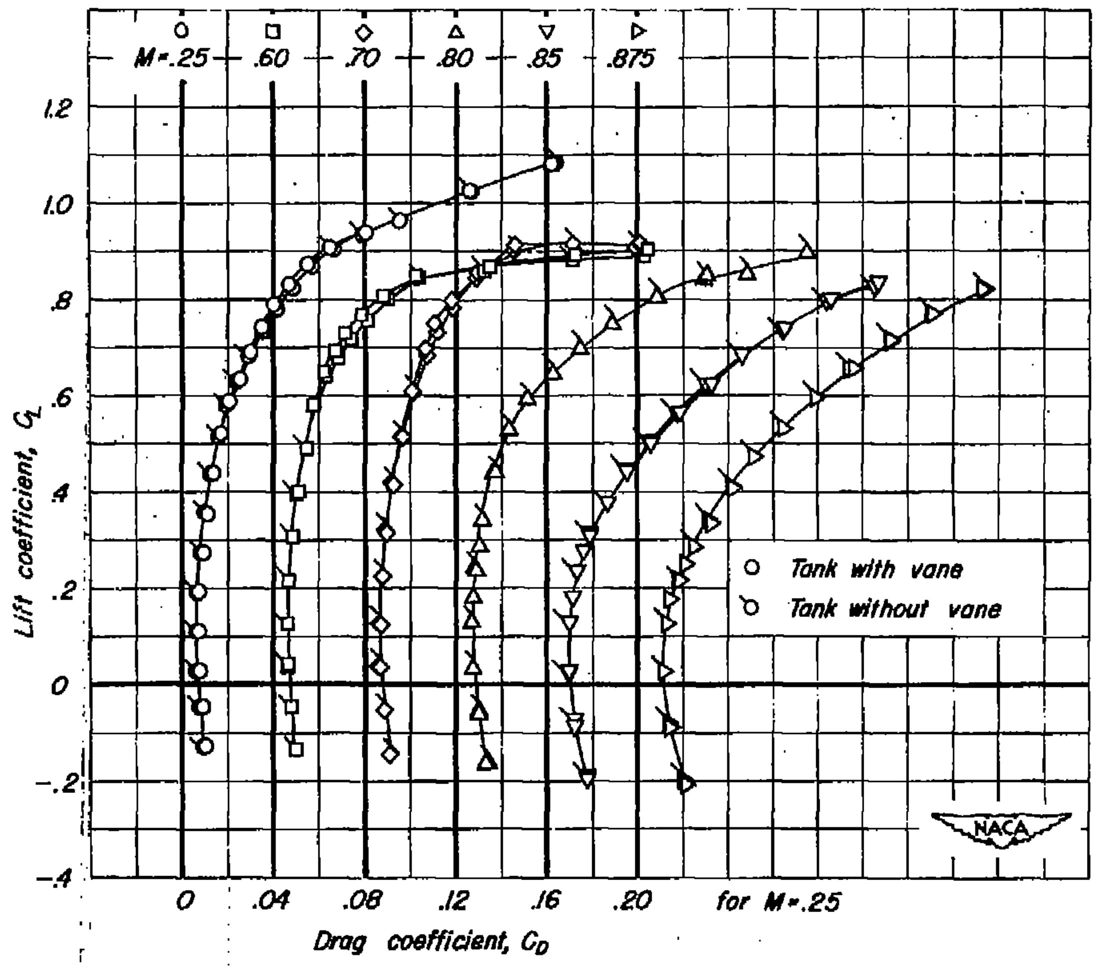
[redacted]



(b) C_L vs C_m.

Figure 12.– Continued.

[redacted]



(c) C_L vs C_D.

Figure 12.- Concluded.

[redacted]